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FINAL REPORT

ADVANCED BEARING STUDY

PART 1. MATERIAL SCREENING TESTS

PREPARED FOR
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CONTRACT NAS3-7943

Pratt & Whitney Aircraft DIVISION OF UNITED AIRCRAFT CORPORATION
FLORIDA RESEARCH AND DEVELOPMENT CENTER

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Prepared for
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30 NOVEMBER 1970

Contractor Program Manager: R. Newton
Contractor Program Advisor: C.R. Comolli
Contractor Test Engineer: R.K. Scrivner

Technical Management
NASA Lewis Research Center
Cleveland, Ohio

Werner R. Britsch
Liquid Rocket Technology Branch

Pratt & Whitney Aircraft DIVISION OF UNITED AIRCRAFT CORPORATION
FLORIDA RESEARCH AND DEVELOPMENT CENTER

FOREWORD

This report was prepared by Pratt & Whitney Aircraft, Division of United Aircraft Corporation, under Contract NAS3-7943 for the Lewis Research Center of the National Aeronautics and Space Administration. The work was administered under the technical direction of the Lewis Research Center's Liquid Rocket Group. Mr. Werner R. Britsch is the NASA Project Manager, and Mr. Herbert W. Scibbe is the NASA Research Advisor.

This report is Part I of a two-part final report, and it was prepared at the conclusion of the Materials Evaluation Phase of the contract. Part II of the final report will be issued after the entire program has been completed.

ABSTRACT

The program described herein was conducted to evaluate several materials that could be used for cages, balls, and races in a cryogenic hydrogen-cooled 110-mm ball bearing. This portion of the program was accomplished using a ball and plate test apparatus, which simulated bearing operation at a DN value of 2.5×10^6 mm-rpm and a thrust load of 20,000 lb.

Three cage lubricant materials (Chemloy 719, Salox M, and Armalon 405-A 116) and two ball and race materials (AISI 440C Steel and Stellite Star J) were evaluated. Initial lubricant testing indicated that Chemloy 719 and Salox M were nearly equal in their performance and superior to the Armalon. The two superior lubricants were tested with various combinations of ball and race materials. The results of these tests indicated that each lubricant performed best with a different combination of ball and race materials.

A complete 110-mm bearing was designed, based on the findings of the ball-plate testing. Bearings of this geometrical design will be purchased in two different material combinations: (1) AISI 440C balls and races and Chemloy 719 cage lubricant; (2) Star J balls and AISI 440C races with Salox M cage lubricant.

The testing of these complete bearings will be reported in the second volume of this Final Report.

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SECTION I
INTRODUCTION

Since the first attempts to use rolling element bearings with liquid hydrogen coolant ten years ago, improvements in bearing design and the use of lubricant materials in bearing cages have resulted in steady increases in bearing life and operating capabilities. However, the larger sizes and increased operating speeds of the advanced turbopumps that are being developed today often exceed the state-of-the-art of bearing development. The high axial loads on the bearings and the high DN levels imposed by the increased speeds and pressures of advanced turbomachinery reduce bearing life to marginal levels with present bearing materials. These limitations imposed by present materials may be overcome by new material combinations to achieve the required useful bearing life for space applications.

One area in which materials improvements can prove very beneficial is that of solid lubricants. When solid lubricants are used as bearing cages, the friction of the rolling element on the cage displaces the lubricant and deposits it on the balls and races providing the lubrication required to operate bearings in an LH_2 environment. P&WA acquired experience in this form of lubrication during our development of the RL10 rocket engine, and under bearing development Contract NAS8-1153 with the George C. Marshall Flight Center. The present program, while oriented in a slightly different direction, has benefitted by the techniques and the ball-plate test rig which were refined in the earlier program.

Another area for possible improvement is that of the materials for balls and races. If sufficiently strong and hard materials with low coefficients of friction can be developed, the requirements for both coolants and lubricants can be reduced with attendant improved bearing life.

This program was established to evaluate the relative performance of cage, race and ball materials in a ball-plate test apparatus at conditions simulating some of the bearing operating parameters and to apply the results of this evaluation to the design of 110-mm bearings.

The testing reported herein includes the evaluation of three teflon-based cage materials (Chemloy 719[1], Salox M[2], and Armalon 405A-111[3]), and two ball and race materials (AISI 440C[4] and Stellite Star J[5]). All tests on these materials were conducted in liquid hydrogen at conditions equivalent to a bearing DN of 2.5×10^6 and an axial load of 20,000 lb.

The material evaluation tests were conducted in two phases, the first, to evaluate the three selected lubricant materials and the second, to test two ball and race materials. In the first phase, the performance of the three lubricants was compared using AISI 440C material for the balls and race. The test results indicated that both Chemloy 719 and Salox M provided better lubrication than Armalon 405A-111 with Chemloy 719 demonstrating the lowest wear rate. It was, therefore, selected as the primary lubricant for the ball and race material testing in phase II. An additional series of tests was conducted using Salox M with the Star J ball and race material.

The material screening tests have been completed and the results are reported herein. From the data obtained, the most promising material combinations were selected for use in the Design and Fabrication of 110-mm bearings. The second volume of this report will cover the actual bearing tests.

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(1) Chemloy 719 is a glass-fiber, MoS_2, Teflon mixture manufactured by Crane Packing Co., Morton Grove, Illinois.

(2) Salox M is a mixture of bronze and Teflon manufactured by Allegheny Plastics, Inc., Coraopolis, Pa.

(3) Armalon 405A-116 is a glass fabric laminated with Teflon manufactured by E. I. DuPont de Nemours & Co., Wilmington, Del.

(4) AISI 440C is a high chromium hardenable steel commonly used for bearings and cutlery.

(5) Stellite Star J is a complex alloy of cobalt and is a product of Haynes Stellite Division of Union Carbide Corp.

SECTION II
SUMMARY OF RESULTS

In this test program, three teflon-based lubricants (Chemloy 719, Salox M, and Armalon) were tested with various combinations of balls and race plates made from AISI 440C and Stellite Star J. Test conditions simulated most of the parameters of a 110-mm bearing run in liquid hydrogen. The series of tests resulted in the following findings:

1. Armalon 405A-116, a laminated glass fiber and Teflon material, failed after 12 and 19 hours when tested with AISI 440C balls and races. The performance of this material was inferior to the others tested.

2. Chemloy 719, a Teflon compound with glass fibers and MoS_2, proved to be the most wear-resistant material of those tested when run with AISI 440C balls and races. When tested with Stellite Star J balls the Chemloy 719 wore at a slightly higher rate than Salox M.

3. Salox M, a teflon base with bronze powder filler, was found to have the lowest wear rate when tested with Stellite Star J balls. It was slightly less wear-resistant than the Chemloy 719 (but was still satisfactory) when used with AISI 440C balls.

4. AISI 440C shows more promise as a race material candidate than does the Stellite Star J material which demonstrated a higher plate wear rate.

5. Star J and AISI 440C have equal merit for use as balls when lubricated by the proper material, i.e., Salox M for Star J balls and Chemloy 719 for AISI 440C balls.

SECTION III
APPARATUS

The ball-plate test apparatus used in this program is shown in figures III-1 and III-2. This apparatus was designed specifically to evaluate ball, race, and cage materials for bearings as well as lubrication methods.

The test section of the apparatus consists of two counter-rotating test disks and a retainer disk. The two test disks contain removable test plates, which are made of the race materials to be evaluated. One of these plates is a smooth flat surface while the other is machined with one or more concentric v-grooves to allow selection of the ball spin rate. These two plates, together with three equally spaced balls, make up the ball and race material test specimens. The retainer disk contains the lubricating inserts, which simulate the ball retainers. Figure III-3 shows the details of the lubricant inserts and ball pocket. The three disks containing the test specimens are located in the center housing through which the liquid hydrogen flows. The central test section is isolated from each of the bearing housings by the helium purged double face seals.

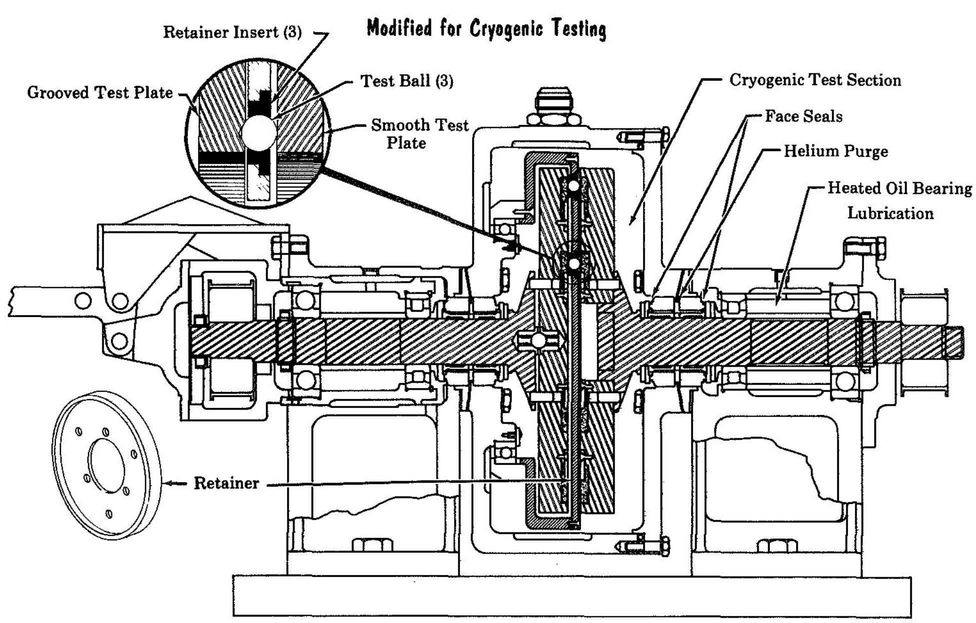

Figure III-1. Ball-Plate Apparatus FD 6728B

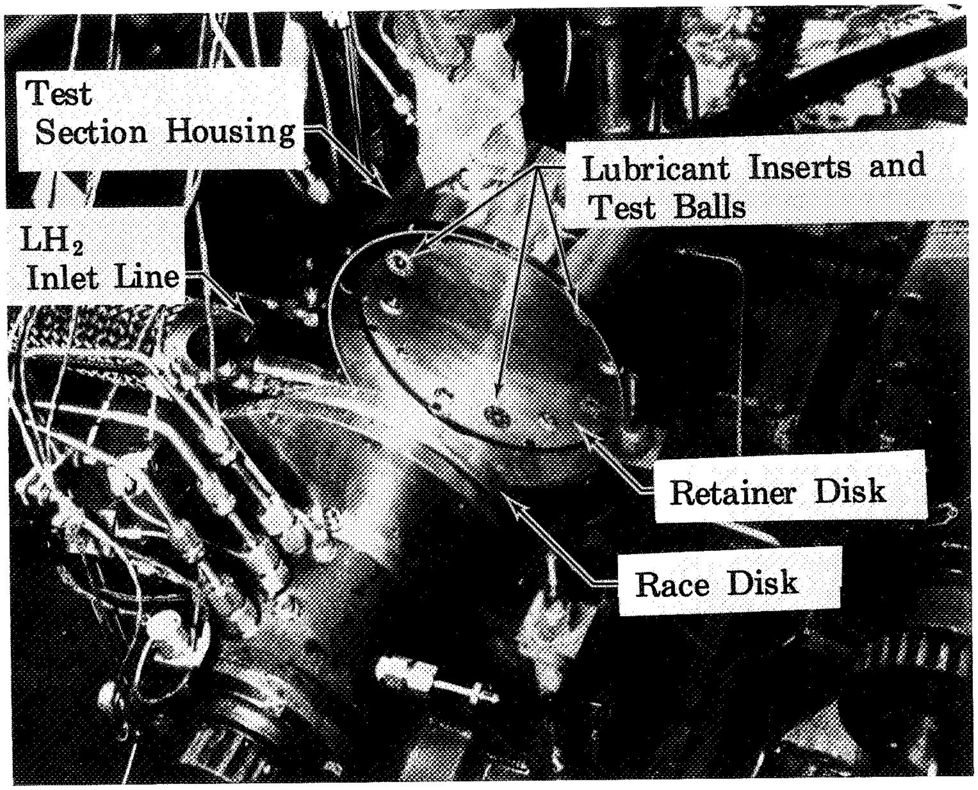

Figure III-2. Closeup of Ball-Plate Test Apparatus Test Section FD 41263

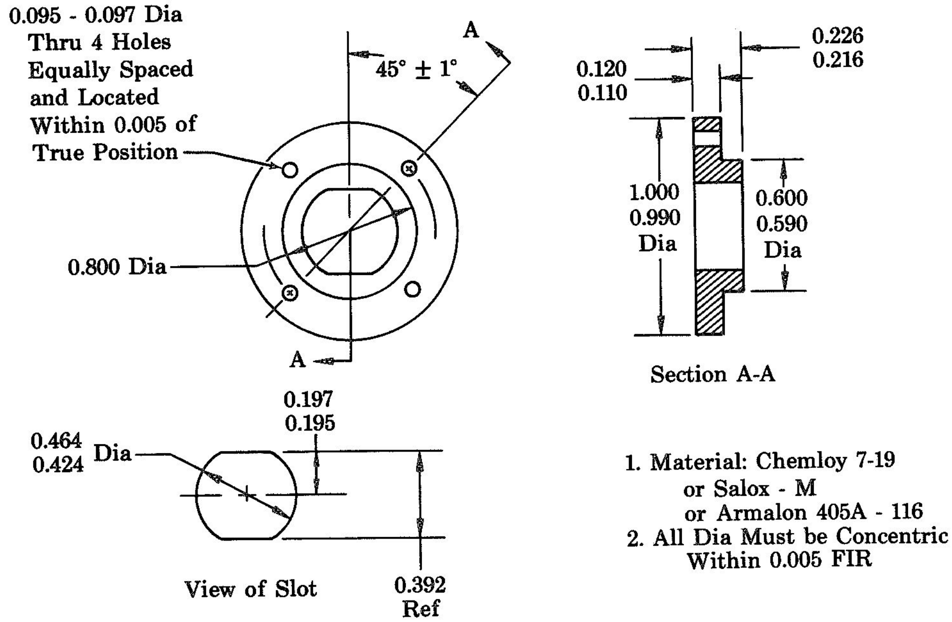

Figure III-3. Insert and Ball Pocket Dimensions FD 24379

The shafts, which carry the test plates, are supported by oil lubricated bearings located in the cylindrical housings on either side of the test section. The shafts are driven by an electric drive through a system of timing belts and a gearbox, which reverses the direction of one of the shafts. Since the driven disks are made to rotate in opposite directions at equal speeds, the retainer disk has little or no rotation and serves only to hold the balls and the inserts. This arrangement also means that a relatively low-speed drive can be used to conduct tests at high equivalent DN values while eliminating centrifugal loads. Accurate control of loading was accomplished by applying selected weights to the loading lever arm shown at the extreme left of figure III-1.

Test specimens are shown at two different radial locations in figure III-1. Either location can be used for a test, and by varying the disk rpm, the required ball rotation velocities can be achieved.

The selection of the required loads, speeds, groove angles, etc., for the best possible simulation was conducted using a computer, as outlined in Appendix A.

For a constant applied weight on the loading lever arm, the Hertzian stress at the ball and grooved plate contact points is a function of the ball diameter and the included angle of the groove. A smaller groove angle will provide a greater difference in the contact point moment arms. With both contact points loaded equally, the spinning moment about the ball vertical centerline will be greater at the larger radius contact point. This larger spinning moment will control and cause the ball to spin, as well as roll around the horizontal axis. The geometry of the ball and groove is shown in Appendix A. (See figure A-3.) The combined spin and Hertzian stress at the ball contacts can cause early bearing failures due to friction and surface fatigue.

Failures of the balls, race plates, and lubricant inserts are all characterized by a rise in vibration levels. To minimize damage to test specimens and to the test rig, an automatic shutdown system was used. This system was based on an accelerometer located on the rig loading arm. An electronic system shut down the rig drive when the accelerations reached a preset level.

Rig control and maintenance of desired test conditions were obtained by measuring:

1. Rig rpm
2. Coolant flow rate
3. Coolant inlet temperature
4. Coolant discharge temperature
5. Rig vibrations
   a. Axial
   b. Horizontal
   c. Vertical
6. Retainer plate rpm
7. Coolant pressure at inlet
8. Coolant pressure at discharge
9. Load arm deflection (relative wear indicator).

SECTION IV
BEARING CAGE LUBRICANT SCREENING TESTS AND SELECTION

A. GENERAL

The objective of this portion of the program was to evaluate three specified bearing cage lubricants using the ball-plate test apparatus and to select the most promising one for use in subsequent testing of ball and race materials. The ball and race material specified as a standard for use in this phase of testing was AISI 440C steel.

Three tests of each lubricant material were to be conducted at simulated operating conditions of a 110-mm bearing operating in liquid hydrogen at a thrust load of 20,000-lb and at a DN value of 2.5×10^6 mm-rpm. The duration of each test was to be twenty hours or until failure, whichever occurred first. Two modes of failure are considered: (1) the lubricant insert may wear through to the aluminum support plate, and (2) a mechanical failure of the test plates or balls. Either of these two failures is detected by a rise in the test apparatus vibrations.

The lubricants specified for evaluation testing were

1. Chemloy 719, a MoS_2-glass fiber filled Teflon (5% MoS_2 and 15% glass fibers by weight)
2. Salox M, a bronze filled Teflon composition (40% bronze by weight)
3. Armalon 405A-116, a Teflon glass fabric laminate.

The Chemloy 719 lubricant successfully completed the three scheduled endurance tests demonstrating good lubricating qualities and a low wear rate. The Salox M also demonstrated good performance during the scheduled endurance tests. In the case of the Salox M, four instead of three tests were conducted to offset two premature test terminations, one due to a ball failure and the other a rig malfunction. The Armalon material consistently demonstrated poor wear resistant qualities; therefore, only two tests were completed and the third was committed to the Salox M evaluation.

A summary of results is presented in the following paragraphs. The test data and test specimen configuration for each test are given in tables B-1 through B-10, Appendix B. Photographs of representative wear of each type of lubricant after completion of testing is shown in figures IV-1 through IV-3.

Figure IV-1 presents a typical Chemloy 719 insert after 19 hours, 56 minutes, showing little ball pocket wear.

Figure IV-2 shows a typical Salox M lubricant insert after 20 hours of testing. Ball pocket wear is well within established limits.

Figure IV-3 shows an Armalon insert after 12 hours and 25 minutes of testing. Note that the wear has penetrated into the aluminum mounting plate.

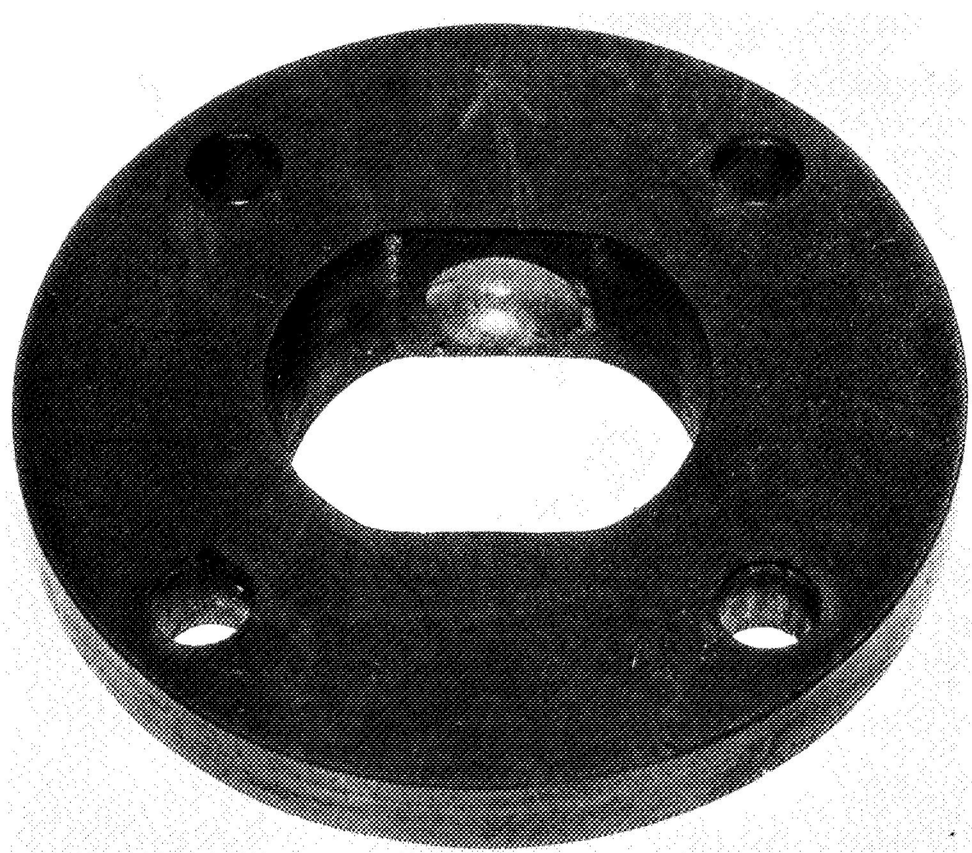

Figure IV-1. Chemloy 719 Insert After 19-hr 56-min Test (Test No. 7)

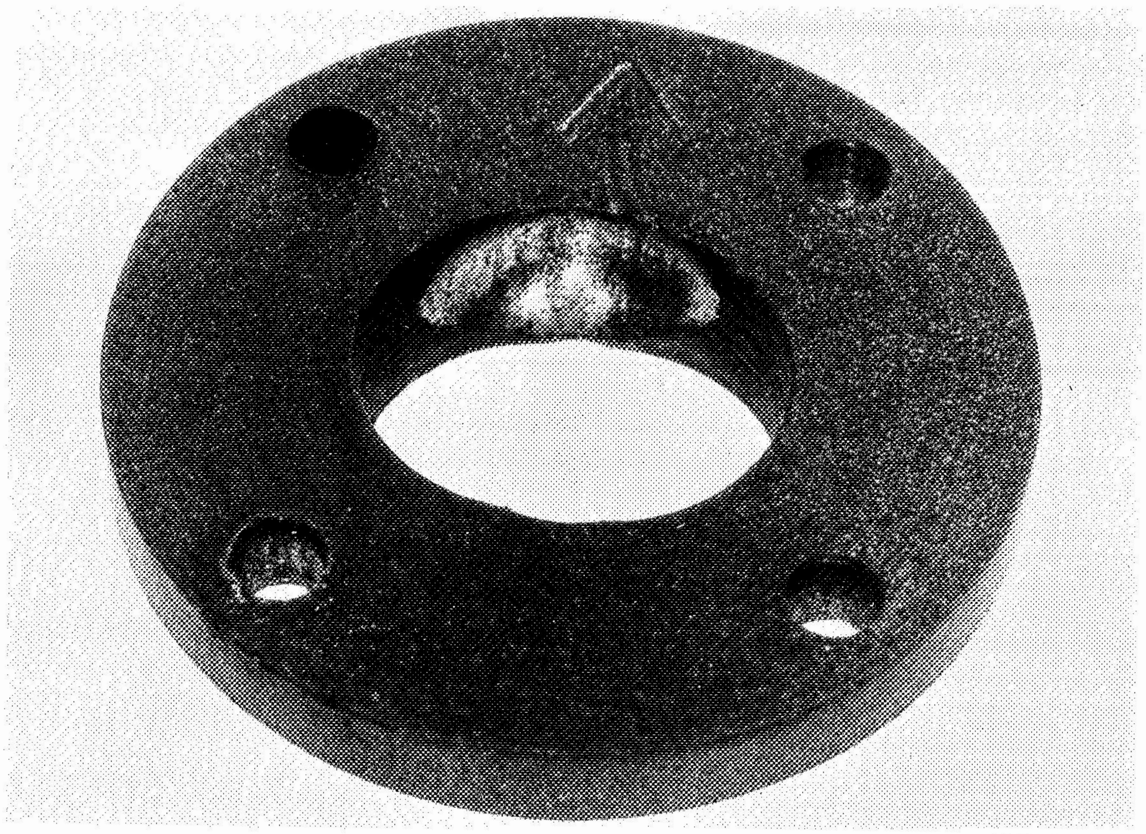

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Figure IV-2. Salox M Insert After 20-hr Test (Test No. 2)

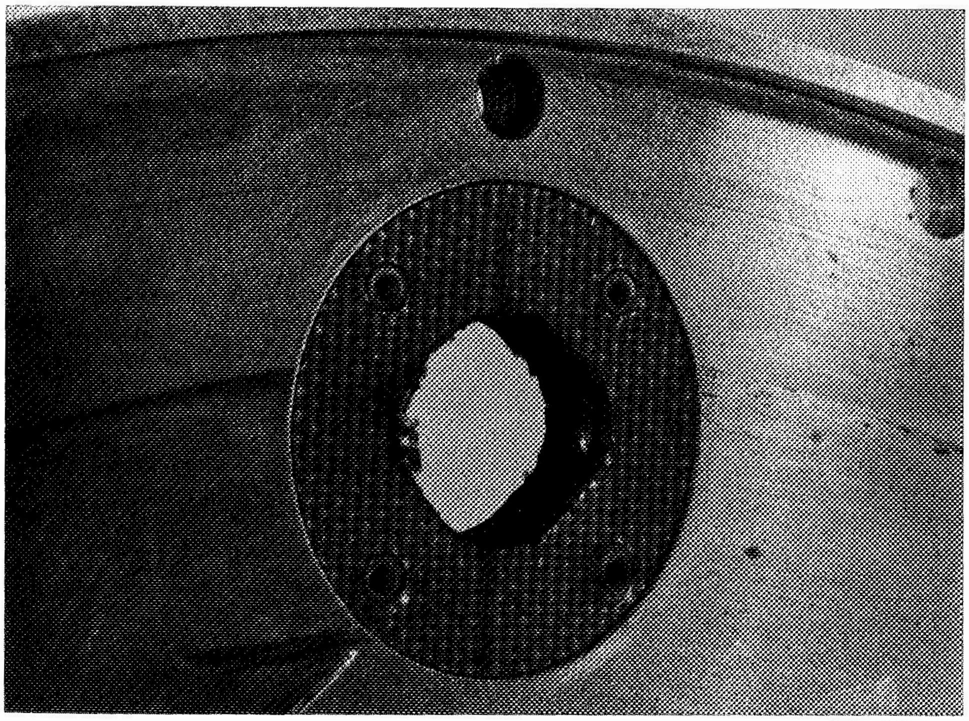

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Figure IV-3. Armalon Insert After 12-hr 25-min Test (Test No. 3)

The ball-plate apparatus, which has two tracks at different radii on each test plate, was operated at 7616 or 8100 rpm (depending on which radius track was in use) to maintain the required ball speed. With an axial load of 116 lb/ball, a Hertz stress of 315,000 psi was experienced by the grooved plates at liquid hydrogen temperatures.

Figure IV-4 presents a surface and cross-section view of an AISI 440C ball that failed by fatigue at the point of an inclusion of foreign material during the initial ball plate testing.

B. TEST ANALYSIS

Analysis of the nine tests performed with Chemloy 719, Salox M, and Armalon when operating with AISI 440C balls and plates shows that the wear rate of Chemloy 719 is slightly lower than that of Salox M. The Armalon is unsatisfactory because it did not complete the 20-hour endurance test that was specified as a standard to evaluate the lubricants. The wear rates on the inserts are shown by the diameter increase and weight loss shown in table IV-1. Data for individual tests are presented in Appendix B.

C. SELECTION OF THE LUBRICANT MATERIAL

Chemloy 719 was selected as the best lubricant material for use in the fabrication of the bearing cages as a result of the testing that was conducted during the lubricant material screening evaluation. In addition to demonstrating a low wear rate, the tensile strength of Chemloy (2300 psi) is approximately that of Salox M (2400 psi), but the lower specific gravity, 2.13 versus 3.16 provides a higher strength to weight ratio. The centrifugal loads in a high speed bearing cage require a high combined strength of the cage material and the retainer. The lower density of Chemloy 719 contributes toward a lower centrifugal load and a higher strength-to-weight ratio, and these in turn combine to reduce the required combined strength and thus the combined weights for the cage and retainer design. These factors, as well as the low wear rate exhibited during the lubricant material screening evaluation tests, resulted in the selection of Chemloy 719 as the cage material for use in the remainder of the ball and race material evaluation tests and the cage material for the first six 100-mm ball bearings to be procured under the contract.

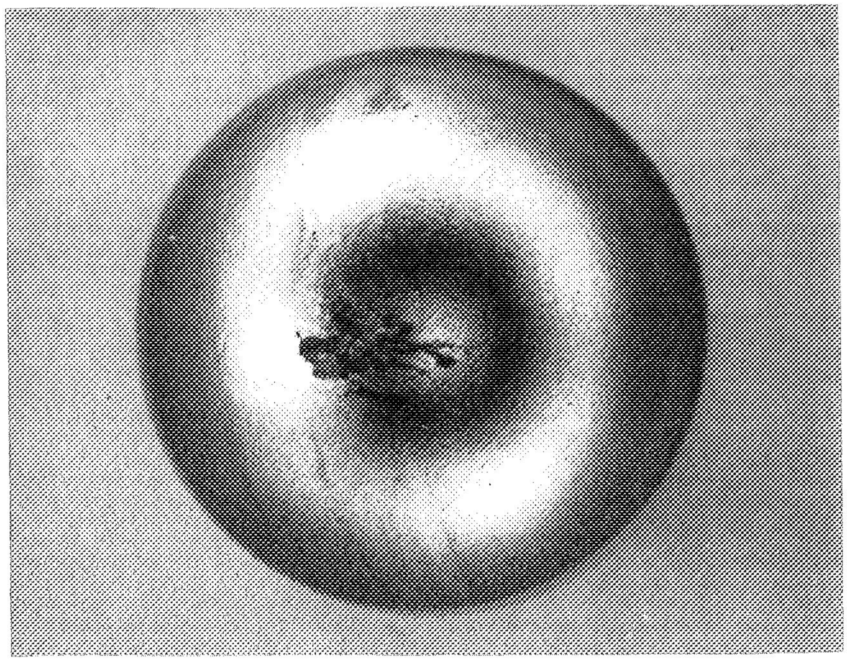

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Figure IV-4a. Overall View of Ball Showing Spalling. The Configuration of the Spalling is not Similar to the Spalling Found in Fatigue (Test No. 4) FL 7761

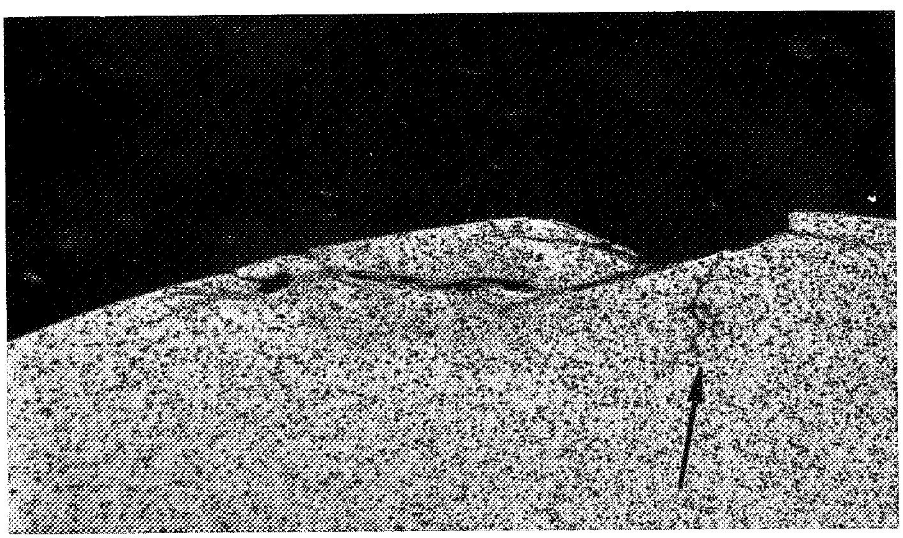

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Figure IV-4b. Transverse View of Spalling Showing Oxide Inclusion (Arrow) FL 7761

Table IV-1. Average Wear and Weight Loss of Test Lubricant Inserts and Balls (Tests No. 1-9)

Insert Material	Test No.	Test Duration, hr	Plate Speed, rpm	Groove Diameter, in.	Hertz Stress on Grooved Plate*, psi	Average Insert Wear, in.	Average Insert Weight Loss, gm	Average Ball Wear, in.	Average Ball Weight Loss, gm
Armalon	3	12.4	7616	8.060	315,000	One Insert 100% wear	**	0.0001	**
Armalon	1	18.7	7616	8.060	315,000	100% wear	**	**	**
Salox	4	4.8	8100	7.520	315,000	0.027	0.040	**	**
Salox	2	20.0	8100	7.520	315,000	0.0641	0.094	0.00001	0.002
Salox	5	10.6	7616	8.060	315,000	Failed Insert (Rig Failure)	**	**	**
Salox	9	20.0	8100	7.520	315,000	0.050	0.062	0.0001	0.0003
Chemloy	6	17.0	8100	7.520	315,000	0.058	0.041	0.0001	0.002
Chemloy	7	19.9	7616	8.060	315,000	0.039	0.008	0.0002	0.0027
Chemloy	8	20.0	8100	7.520	315,000	0.048	0.002	0.0000	0.0023

*Based on the modulus of elasticity at liquid hydrogen temperatures.
**See test comments in tables B-1 through B-9.

SECTION V
BALL AND RACE MATERIAL TESTS AND SELECTION USING CHEMLOY 719 LUBRICANT MATERIAL

A. GENERAL

As a result of the cage lubricant screening that is reported in Section IV of this report, Chemloy 719 (a mixture of Teflon, glass fiber, and molybdenum disulfide) was selected and used for the ball-and-race material evaluation tests in the ball-plate test apparatus. Two different materials, Stellite Star J and AISI 440C steel, were evaluated as candidates for bearing balls and races. The four combinations tested with Chemloy 719 were (1) AISI 440C balls and races, (2) AISI 440C balls and Star J races, (3) Star J balls and races, and (4) Star J balls and AISI 440C races.

Test data from the three tests using Chemloy 719 in the lubricant screening phase were used for the AISI 440C ball and race evaluation. Tests of three of each of the other combinations were conducted in liquid hydrogen with the same operating parameters of the ball-plate apparatus that were used in the lubricant evaluation. Each test was scheduled for 20 hours duration, or until failure, whichever occurred first. Seven of the additional nine tests completed the 20-hour endurance requirement. Two tests were stopped prematurely because of ball failures. Both test failures were with Star J balls rolling on AISI 440C plates and occurred after 11 and 14 hours of testing, respectively.

The results of all of the ball and race material tests using Chemloy 719 as the lubricant are presented in this section and are summarized in table V-1. Detailed test results are presented in tables in Appendix B.

B. FACTORS CONSIDERED IN THE TEST PROGRAM AND ANALYSIS OF TEST DATA

The parameters used to assess and compare the various material combinations were

1. Surface condition after test
2. Subsurface microstructure in contact areas
3. Degree of wear
4. Hardness of critical areas
5. Weight loss of lubricant inserts
6. Vibration as function of time.

Table V-1. Average Wear and Weight Loss of Test Balls and Chemloy 719 Lubricant Inserts*

Material Combination	Test No.	Test Duration, hr	Average Ball Wear, in.	Average Ball Weight Loss, gm	Average Ball Weight Loss, %	Average Insert Wear, in.	Average Insert Weight Loss, gm
AISI 440C Plates	6	17.0	0.0001	0.001	0.04	0.058	0.041
AISI 440C Balls	7	19.9	0.0002	0.003	0.08	0.039	0.008
	8	20.0	0.0001	0.002	0.07	0.048	0.017
Average 3 Tests			0.0001	0.002	0.06	0.048	0.022
AISI 440C Plates	10	14.0	Failed	Failed	Failed	Destroyed	Destroyed
Star J Balls	11	11.5	0.00017**	0.0002**	0.004**	0.1038	0.1703
	12	20.0	0.00013	0.0004	0.011	***	***
Average 2 Tests			0.00015	0.0003	0.008		
Star J Plates	13	20.0	0.00027	0.0033	0.094	0.1573	0.2557
AISI 440C Balls	14	20.0	0.00060	0.0019	0.055	0.1183	0.1467
	15	20.0	0.00127	0.0035	0.101	0.0532	0.0264
Average 3 Tests			0.00071	0.0029	0.083	0.1096	0.1429
Star J Plates	16	20.0	0.00080	0.0047	0.119	***	***
Star J Balls	17	20.0	0.00007	0.0005	0.013	0.0170	0.0013
	18	20.0	0.00083	0.0027	0.070	0.0542	0.0429
Average 3 Tests			0.00057	0.0026	0.067	0.0356	0.0221

*The data used to compile this table can be found in tables IV-2 through IV-13.
**One ball, taken for laboratory analysis, not included in data; test duration, 11.5-hr.
***Inserts worn through to the aluminum retaining plate.

The results of the analyses of each factor are discussed in the following paragraphs.

1. Surface Condition After Testing

Photomicrographs were made of the surface of one ball and the flat plate from each test. Of these, one set of photomicrographs was chosen as representative of the particular combination of materials; these are presented in figures V-1 through V-4.

a. Chemloy 719 with AISI 440C Balls and Plates

Figure V-1 shows photomicrographs of the surfaces of a ball and a plate of AISI 440C after twenty hours of testing in liquid hydrogen with Chemloy 719 lubricant in test No. 7. The dark color of the ball track on the flat plate shown is typical of that experienced in most of the ball-plate tests that were conducted under this program. The dark color is caused by the mechanical transfer of the Chemloy 719 from the cage to the balls and the flat plate.

The wear pattern shown is generally parallel to a fixed plane through the ball, and is typical of that exhibited by most of the balls tested during this program. With reference to a coordinate system with its origin at the ball center and one of its coordinate axes aligned with the line-of-centers of the ball and the test rig axis of rotation, the ball appears to have been operating in a pure rolling mode. Referring to figure A-3 in Appendix A, it is evident that if the plate is being rotated about its center and the ball is held essentially motionless in the plane parallel to the plate, the outer ball contact point in the groove will be traveling faster than the inner contact point. This creates a moment that will cause the ball to spin about a ball axis that is perpendicular to the plane of the plate unless slippage occurs at one or both of the contact points. Assuming that the parallel wear paths represent pure rolling, slippage must have occurred. The rolling condition concentrated the load cycles to paths parallel to a fixed plane through the ball. This imposed a more severe surface fatigue test on the balls than would be experienced in an actual bearing where ball spin distributes the surface load cycles over the entire surface. The slight darkening of the ball in figure V-1 is caused

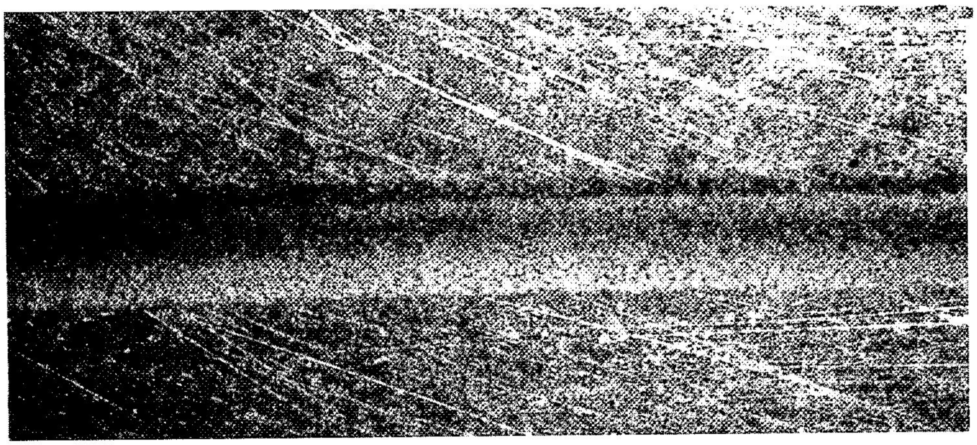

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Figure V-1a. AISI 440C Flat Plate Wear Pattern (Test No. 7) FD 15522

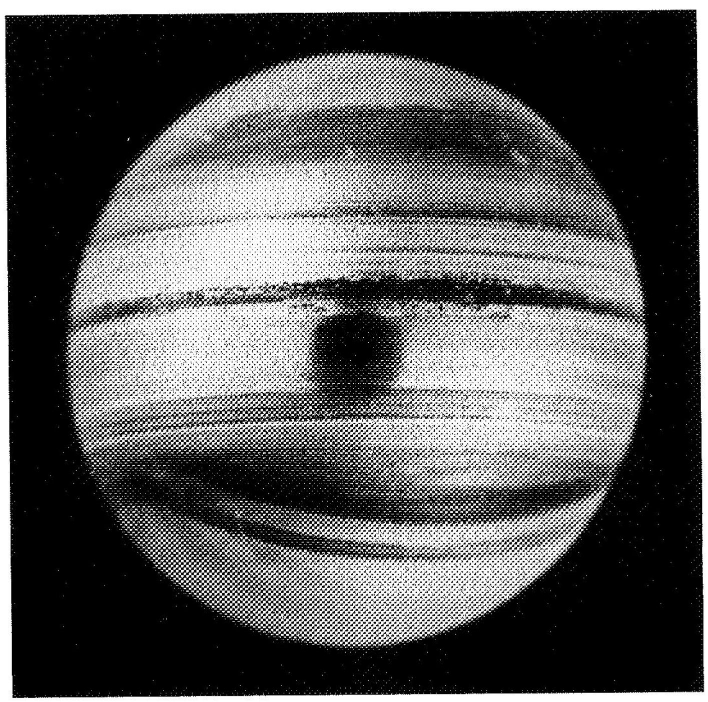

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Figure V-1b. AISI 440C Ball Wear Pattern (Test No. 7) FD 15522 by smears of Chemloy 719. Surface conditions of plates and balls were considered excellent.

b. Chemloy 719 with Star J Balls and AISI 440C Plates

Figure V-2 presents photomicrographs of the surfaces of a Star J ball and the AISI 440C flat plate on which it was run for 20 hours in test No. 12. Again, ball spin apparently was not present and a fixed wear path was generated. The surface of the ball is slightly colored and small bits of Chemloy 719 can be seen adhering to the surface. There is evidence of a slight roughening of the ball surface in the form of minute pits (unlike spalling, which is common to a bearing material such as AISI 440C). This condition does not appear to be a result of asperity welding. The flat AISI 440C plate shows only a slight wear path as in previous tests with AISI 440C balls.

The other two tests of this material combination (tests No. 10 and 11) completed only 14 and 11.5 hours before a ball failure ended each test. A laboratory analysis of the balls used in these tests is included at the end of this section as paragraph D.

c. Chemloy 719 with AISI 440C Balls and Star J Plates

Figure V-3 presents photomicrographs of the surfaces of an AISI 440C ball and a Star J flat plate that completed 20 hours in test No. 14. The flat plate shows normal wear with no surface distress. The AISI 440C ball shows two distinct paths of wear. This is attributed to a reorientation of the ball after a routine inspection during the test program. The surface of the ball shows normal wear with some discoloration due to deposits of Chemloy 719.

d. Chemloy 719 with Star J Balls and Plates

Figure V-4 presents photomicrographs of the surfaces of a ball and plate made of Star J, tested for 20 hours during test No. 16. The flat plate from this test appears normal with no surface distress evident. The Star J ball shows three wear tracks and is attributed to ball reorientation after routine examinations during the test program. The ball shows signs of surface roughening in the wear zone. This roughness appears to be somewhat similar to the spalling of AISI 440C materials, but apparently is not detrimental to the operation of the ball.

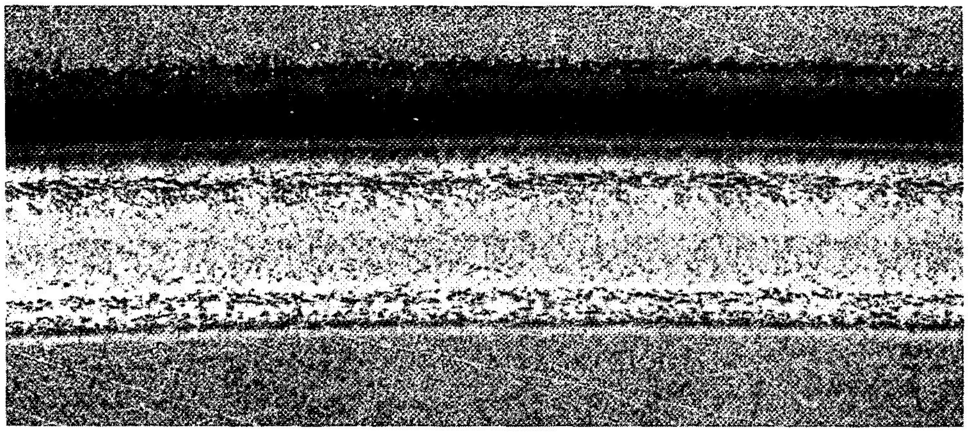

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Figure V-2a. AISI 440C Flat Plate Wear Pattern (Test No. 12) FD 15524

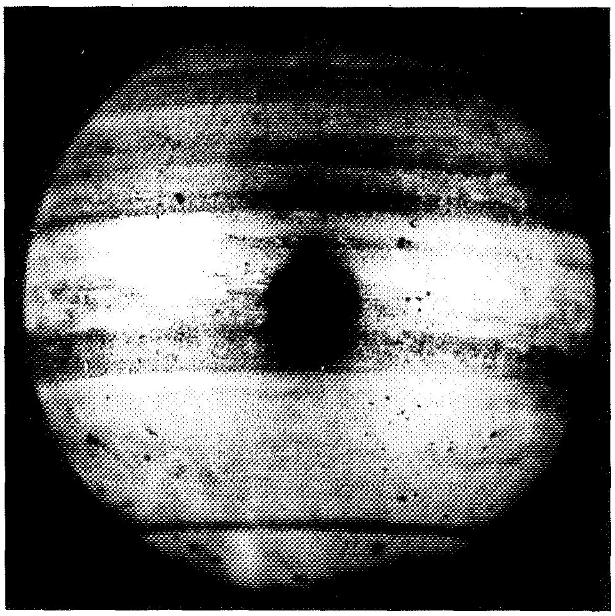

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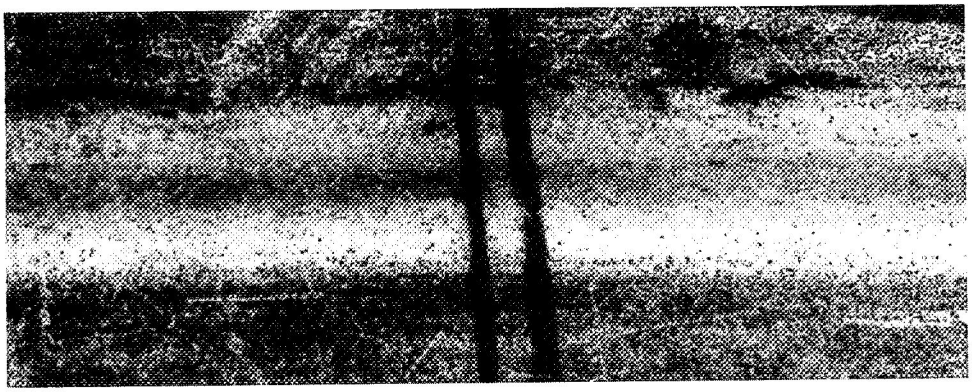
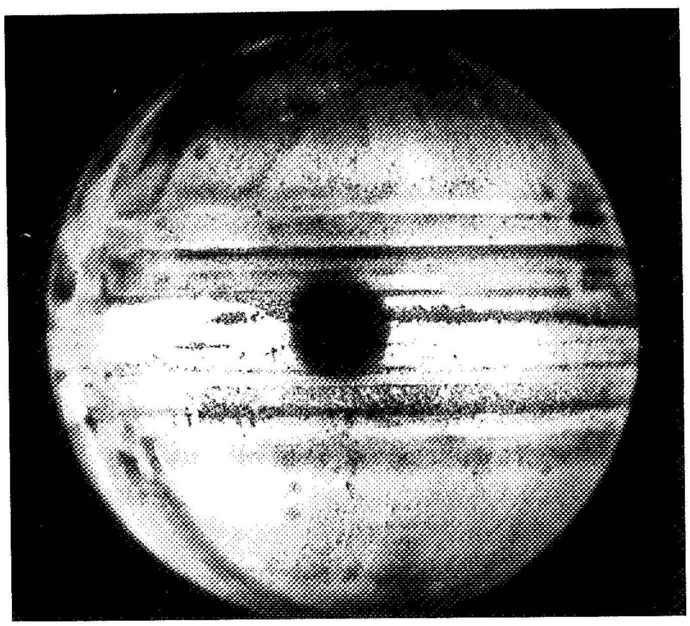
Figure V-2b. Star J Ball Wear Pattern (Test No. 12) FD 15524



(MAG: 8X)

Figure V-3a. Star J Flat Plate Wear Pattern (Test No. 14)

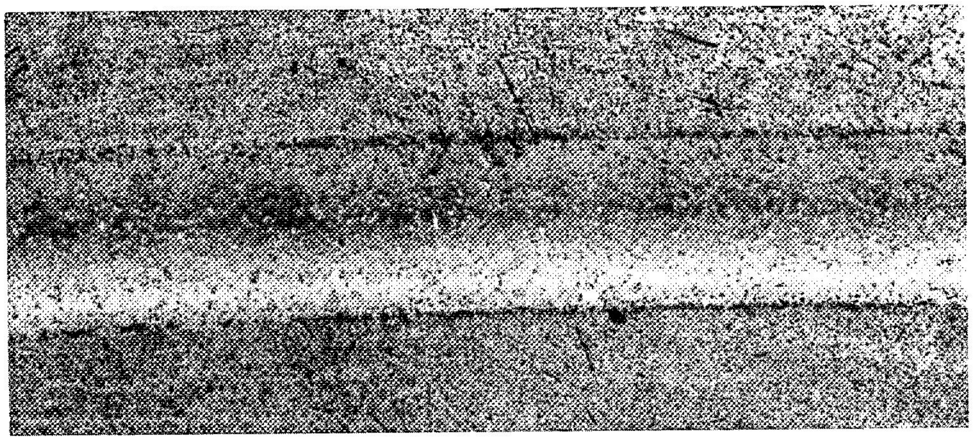
FD 15521



(MAG: 8X)

Figure V-3b. AISI 440C Ball Wear Pattern (Test No. 14)

FD 15521



(MAG: 8X)

Figure V-4a. Star J Flat Plate Wear Pattern (Test No. 16)

FD 15523

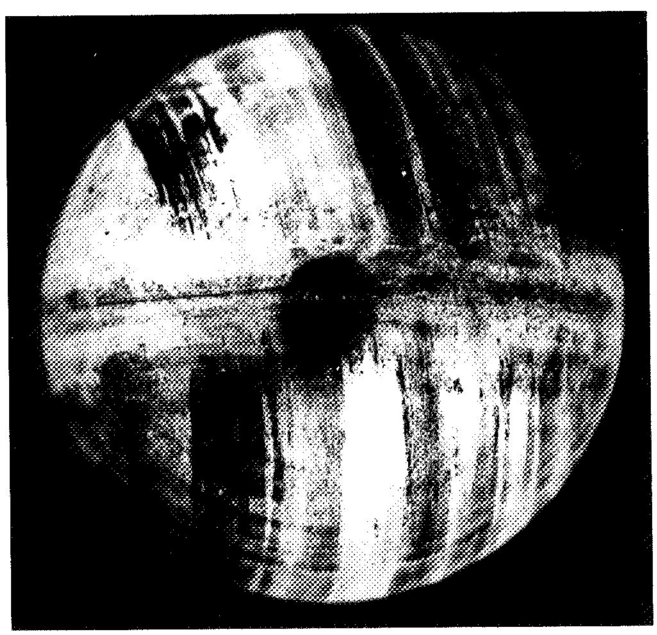


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Figure V-4b. Star J Ball Wear Pattern (Test No. 16)

FD 15523

Based on the surface condition of the balls and plates that were tested with Chemloy 719 lubricant in the ball-plate apparatus, it appears that of the materials tested the best combination for use with Chemloy 719 lubricant in full-scale bearings is AISI 440C balls and AISI 440C races.

2. Subsurface Microstructure in Contact Areas

A post-test subsurface microscopic examination was made on all ball and plate test samples both before and after etching. The balls and plates were sectioned to reveal the subsurface zone. The subsurface zone is approximately 0.020-in. deep, and is the area in which bearing fatigue failures normally originate. No evidence of subsurface distress or cracks caused by fatigue was noted in any of these samples. Photos of representative sectioned AISI 440C and Star J balls are presented in figure V-5. As can be seen, the Star J is made up of fine needlelike crystals somewhat larger than the more homogeneous structure of the AISI 440C balls. The difficulty in controlling the grain size of the Star J material is evident in figure V-6 which shows the grain structure of a Star J ball that failed during test. In this ball the needle crystals were enlarged, probably due to a low cooling rate.

Typical microstructures of AISI 440C and Star J plates are shown in figure V-7. Again the AISI 440C structure is fine grained and homogeneous while the Star J shows even longer needlelike crystals than that of the balls. This is probably caused by the slower cooling of the large centrifugal casting used for the plate material.

While the subsurface examination of the microstructure of the test samples did not reveal fatigue cracks in either material, the AISI 440C material is considered more suitable because the structure is more controllable than the Star J. Grain structure of the two metals is discussed further on page V-23.

3. Degree of Wear

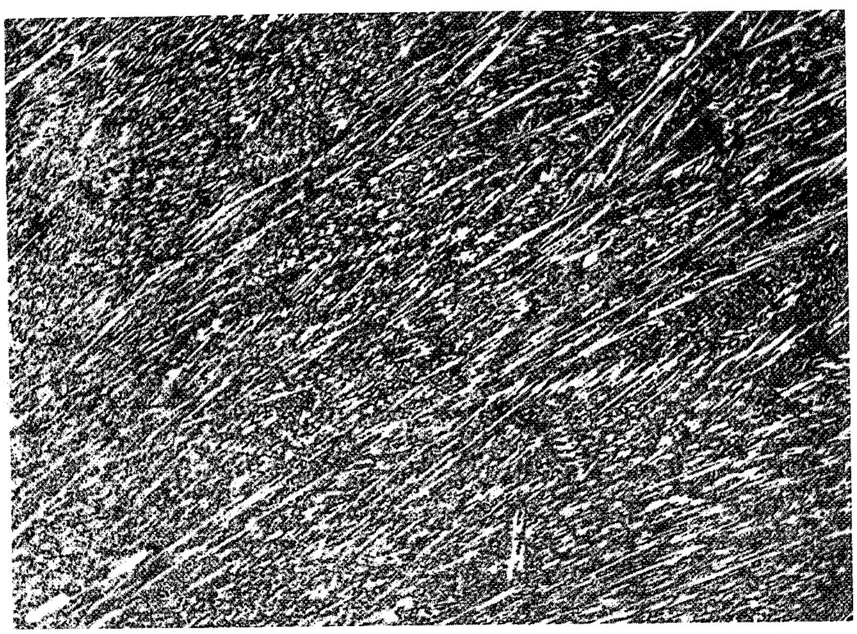
Evaluation of the wear experienced by the test samples was made by different means for the balls and plates as described below.

a. Test Balls

The wear on the balls was measured by dimensional inspection and weight change. The reduction in ball diameter and weight loss of the balls were determined in the following manner:

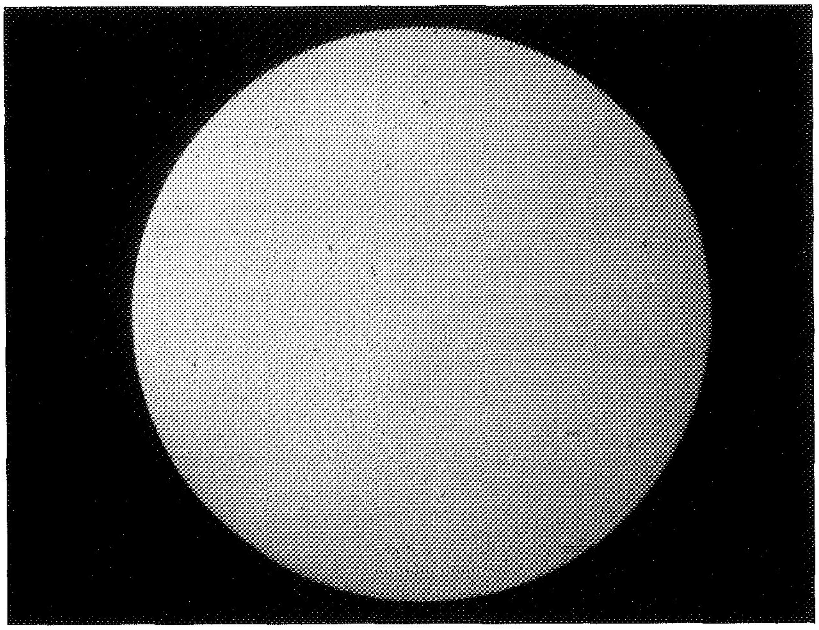
(MAG 100X)

Figure V-5a. Characteristic Microstructure AISI 440C Ball FD 15520



(MAG: 100X)

Figure V-5b. Characteristic Microstructure Star J Ball FD 15520



(MAG: 8X)
FL 8393

Figure V-6a. Cross-Sectional View of Star J Ball Showing Porosity on Ball Surface (Test No. 11)

(MAG: 75X)
FL 8393

Figure V-6b. Sectional View of Star J Ball Showing Porosity at Arrows and Revealing Needles Where Fracturing Occurred (Test No. 11)

(MAG: 100X)

Figure V-7a. Characteristic Microstructure AISI 440C Flat Plate FD 15519

(MAG 100X)

Figure V-7b. Characteristic Microstructure Star J Flat Plate FD 15519

1. Reduction in ball diameter was determined by use of an "Electro Limit" Ball Measurement Gage, which has the capability of directly measuring ball diameter to an accuracy of 0.00002 inch; measurements were taken across the wear path whenever possible.
2. Weight loss of the balls was determined by using a Mettler Instrument Company precision balance, which has the capability of weighing to an accuracy of 0.0001 gram; weight readings were made before and after each test.

(1) Ball Diameter

As indicated in tables B-6 through B-8, ball diameter was only measured to four significant figures in the tests of the AISI 440C balls and plates. These tests were made early in the program before it was learned from experience that greater precision was required for proper correlation of the test data. The samples, having been sectioned for other tests and/or sent to NASA-LeRC for evaluation, are no longer available for remeasurement. In the later tests reported in tables B-10 through B-18, ball diameter was measured to five significant figures. Comparison of these data in table V-1 indicates a trend that the AISI 440C balls rolling on AISI 440C plates experience the smallest diameter change.

(2) Ball Weight

As with the diameter measurements described above, the weight measurements of the balls were made with greater precision in the later tests than in the earlier AISI 440C ball and plate tests (0.0001 vs 0.001 gram). This introduces some uncertainty in accurate evaluation of the data; nonetheless, trends are not significant enough to provide a good comparison. Star J has a density approximately 15% greater than AISI 440C; consequently, the percent weight change method of comparison is more significant than the actual weight change. As may be seen in table V-1, the average percent weight change is very small for all the materials, ranging from 0.008 to 0.083%. The smallest percent weight loss value (0.008%) is associated with the Star J ball and AISI 440C plate combination. However, this is based on only one completed 20-hour test, since the other two tests of this combination of ball and plate material experienced ball failures. (See paragraph D at the end of this section). Because of the limited data and high failure rate, this combination of materials was not considered a good combination for use with Chemloy 719 lubricant. Of the remaining combinations of ball and plate materials, the AISI 440C balls on AISI 440C plates show a small advantage over the Star J balls on Star J plates.

On the basis of the inconclusive ball wear data, it was decided that neither of the materials holds a significant advantage over the other. More extensive testing would be required to provide the necessary data.

b. Test Plates

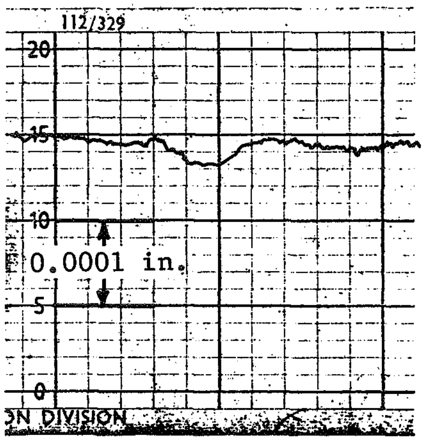
Since the loading on the flat surface was higher and surface wear was more easily measured than on the grooved plates, analysis of plate wear was conducted considering the flat plates only. Surface wear measurements were made using a Taylor Hobson Surface Micrometer, which traces the surface irregularities and presents the magnified trace on a tape. The traces (see figures V-8 and V-9) show wear track depth ranging from 0.00004 to 0.00017 inch below the original surface with a small pile-up of material on the edge of the track in some tests. The average wear track depth below the original surface is in the following summary.

Plate Material	Ball Material	Average Wear Track Depth, in.
AISI 440C	AISI 440C	0.00003
AISI 440C	Star J	0.00006*
Star J	AISI 440C	0.00017
Star J	Star J	0.00017

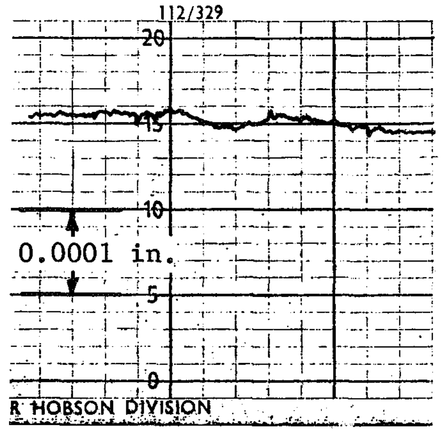
*Based on one 20-hour test.

Comparison of the data from these tests indicates that the combination of AISI 440C balls and AISI 440C plates produced a lower wear rate than for the other combinations tested when lubricated with Chemloy 719.

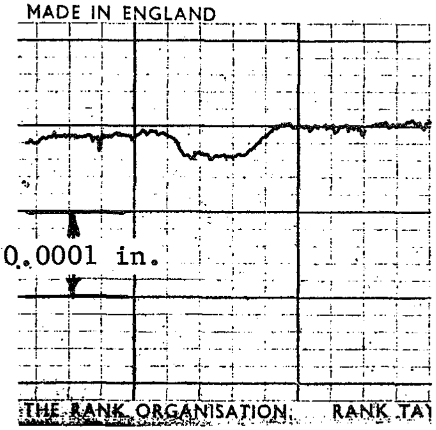
Taylor Hobson Surface Micrometer



Test No. 6, 17 Hours



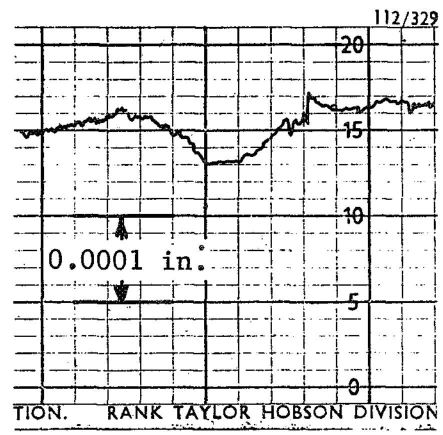
Test No. 7, 19.9 Hours



Test No. 8, 20 Hours

AISI 440C PLATES AFTER RUNNING WITH AISI 440C BALLS

The flat plate surface wear of tests No. 10 and 11 could not be measured due to surface irregularities caused by the ball failure of Test No. 10.

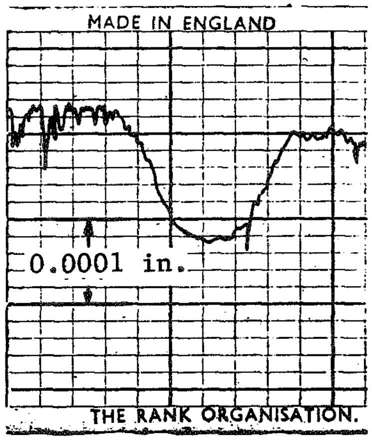


Test No. 12, 20 Hours

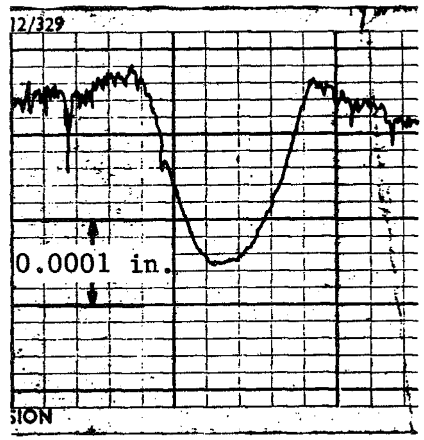
AISI 440C PLATES AFTER RUNNING WITH STAR J BALLS

Figure V-8. Flat Plate Wear Groove Depth, Tests No. 6, 7, 8, and 12 FD 15525A

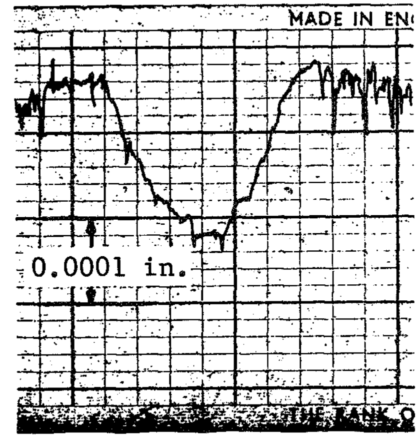
(Taylor Hobson Surface Micrometer)



Test No. 13, 20 Hours

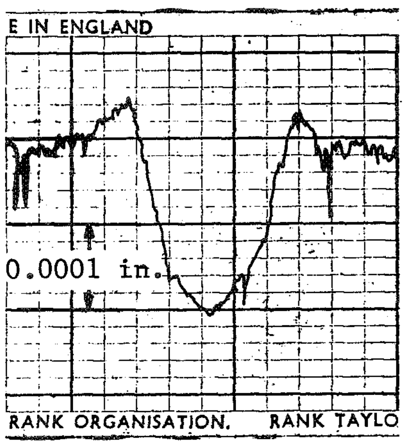


Test No. 14, 20 Hours

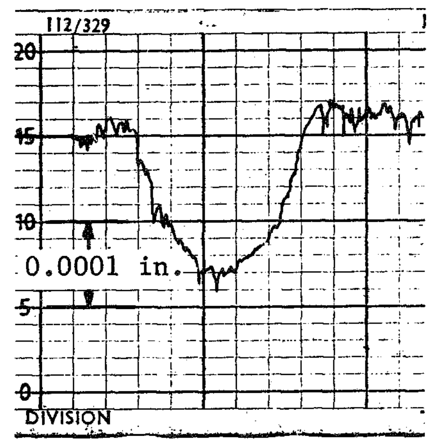


Test No. 15, 20 Hours

STAR J PLATES AFTER RUNNING WITH AISI 440C BALLS



Test No. 16, 20 Hours



Test No. 18, 20 Hours

STAR J PLATES AFTER RUNNING WITH STAR J BALLS

Figure V-9. Flat Plate Wear Groove Depth, Tests No. 13 through 18. FD 15526A

4. Hardness of Critical Areas

a. Test Plates

To investigate a possible change of hardness due to cold working of the flat plate surfaces by the action of the balls, the surface hardness of the sample plates was checked before and after testing. A Rockwell hardness tester was used for both pretest and post-test checks. To prevent damage to the test surface, the pretest checks were made on the back face of the plate samples. Post-test checks were made on the test face both in and adjacent to the wear path of the flat plates. The post-test averages were obtained from data taken at three locations 120 degrees apart. Three readings were made at each location: one just inside of the wear path, one in the wear path, and one just outside of the wear path. Table V-2 presents the average values recorded.

Hardness of the grooved plates was measured initially on the back face. After testing, the hardness of the wear path could not be measured on the grooved plate because of interference between the plate and the hardness tester conical point. Therefore, the hardness of these plates was measured on a sectioned surface near the ball path.

The data on table V-2 do not show a pattern in the change of hardness in the test plates; therefore, no significance was attached to this analysis factor.

b. Test Balls

Ball hardness was not measured before testing since this would have marred the ball surface. The minimum hardness as certified by the vendor is recorded in the table as pretest data. Post-test hardness was measured on a flat surface of the ball after it had been sectioned rather than on the spherical surface of the ball. Comparison of the ball hardness data was not deemed valid because pretest hardness data were only that guaranteed as a minimum by the manufacturer.

An overall analysis of the hardness data shows that the scatter of the individual readings amounts to ± 3 points of the average. Therefore, no significance was attached to this analysis factor.

Table V-2. Average Rockwell C Hardness of Test Balls and Plates

Material Combination	Test No.	Pretest	Flat Plate*** Post-Test Beside Track	Flat Plate*** Post-Test in Track	Grooved Plate Pretest	Grooved Plate Post-Test*	Balls Pretest**	Balls Post-Test*
AISI 440C Plates	6	58	57	58	58	58.5	56	58.0
AISI 440C Balls	7	58	56	55	58	58.5	56	58.5
	8	58	55	55	58	58.0	56	58.0
AISI 440C Plates	10	58	Failed	Failed	58	Failed	57	Failed
Star J Balls	11	58	56	55	58	58	57	62.0
	12	58	55	55	58	58	57	63.0
Star J Plates	13	59	57	56	58	58.5	56	58.0
AISI 440C Balls	14	59	57	58	59	59.0	56	57.5
	15	59	59	58	59	59.0	56	58.0
Star J Plates	16	59	58	57	58	58.5	57	63.5
Star J Balls	17	60	60	58	57	57.5	57	62.0
	18	60	60	60	57	57.5	57	62.0

*Hardness data were taken from sectioned balls and grooved plate.
**Minimum hardness as certified by the vendor. Pretest hardness could not be actually determined from balls used in the test without destroying the surface finish and sphericity of the ball; therefore, this reading is not considered adequate for a good comparison.
***Post-test hardness was averaged for 3 points in the track, and for 6 points (3 on ID and 3 points on OD) of ball track.

5. Wear on Lubricant Inserts

As with the balls, two methods of measuring wear rate were used in the tests on the Chemloy 719 lubricant samples: direct measurement of the inside diameter of the ball pocket, and weight of the lubricant insert before and after testing. The photograph (see figure V-10) of a typical insert shows the wear experienced during a 20-hour test. Individual insert data are shown in tables B-10 through B-18, and in B-6 through B-8. The average data for the tests are presented in table V-1. A study of table V-1 reveals that the data are inconclusive , due somewhat (1) to failures when Star J balls were tested and (2) to an insufficient number of data samples. The average wear of the inserts was lowest with AISI 440C balls and plates; this low wear was followed closely by that of the inserts used with Star J balls and plates. In both cases, individual tests gave erratic wear rates. Because of the erratic wear rates recorded and the limited valid tests made using Star J balls, this analysis factor did not show a decided advantage for any material combination.

6. Vibration as a Function of Time

Plots of test apparatus vibration, as measured by an axial accelerometer on the loading end of the test, are presented in figures V-11 through V-14. As can be seen, the vibrations are erratic over the period of test. Except where failure of a component is occurring as in tests No. 10 and 11 on figure V-12, variation in vibration is believed to be due to particles of lubricant that are deposited on the plate and on the ball track, and the subsequent wearing and smoothing of these lubricant particles as the balls roll over them.

An insufficient number of tests were performed to establish this as an analysis factor.

C. CONCLUSIONS

From the analysis of the six parameters presented in the preceding paragraphs, the following conclusions were reached for the ball-plate testing using Chemloy 719 for the lubricant insert material.

1. Surface Condition

On the basis of the surface appearance of the test items after test, Star J and AISI 440C are comparable in performance as ball and race materials.

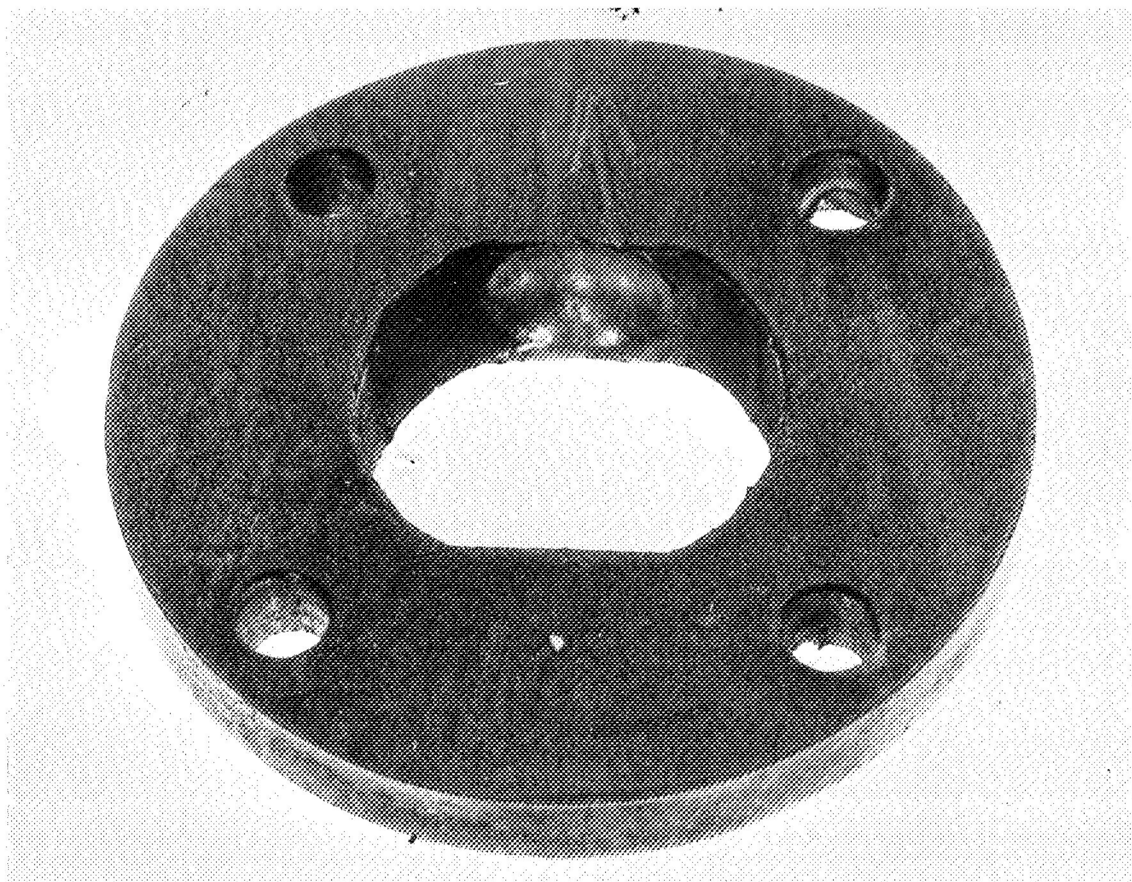


Figure V-10. Chemloy 719 Insert After 20-hr Test With AISI 440C Balls and Plates (Test No. 6) FE 54532

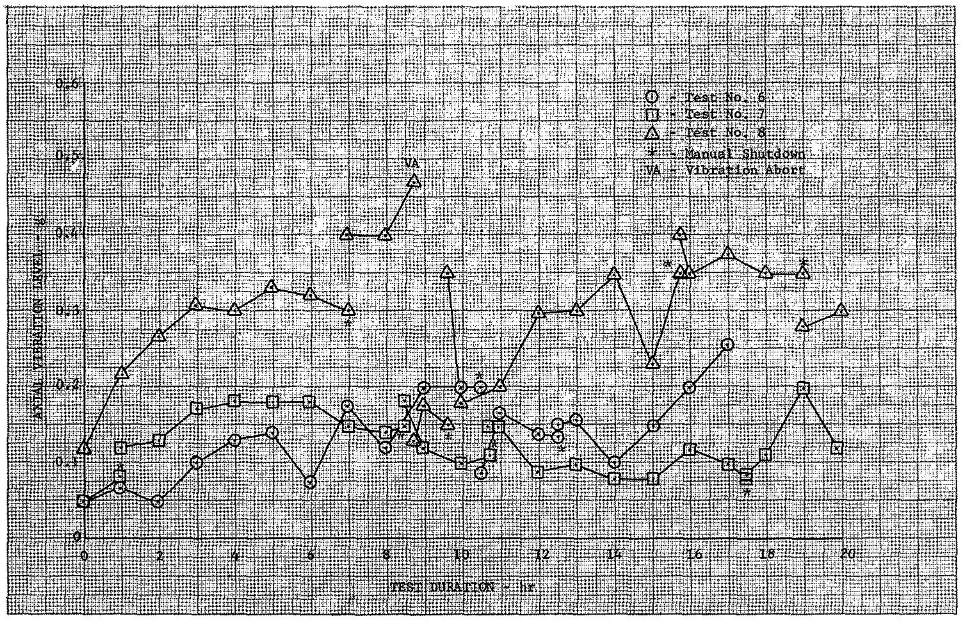


Figure V-11. Vibration Level vs Time - AISI 440C Balls and Plates DF 47307

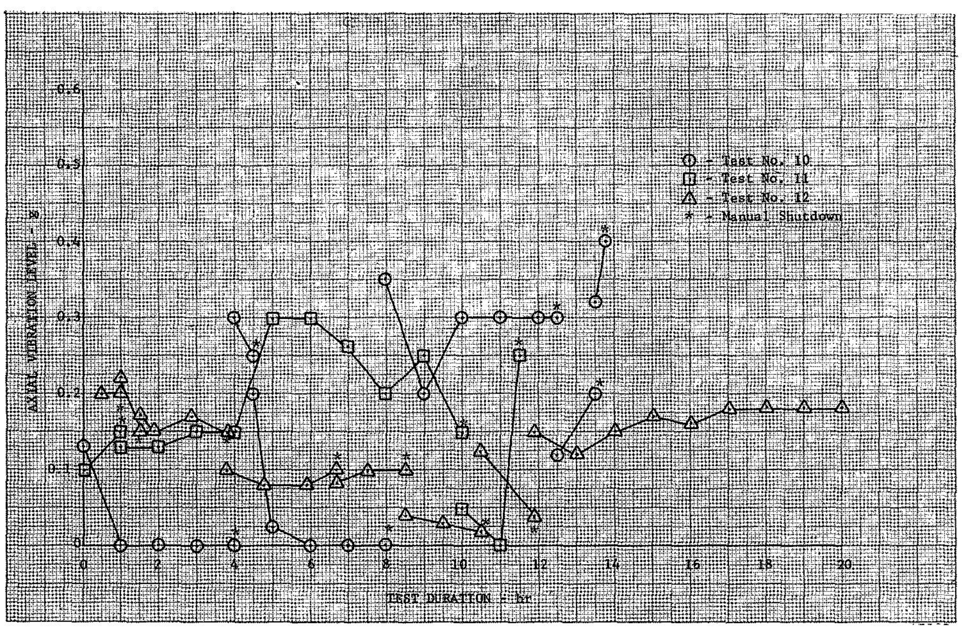


Figure V-12. Vibration Level vs Time - Star J Balls and AISI 440C Plates DF 47308

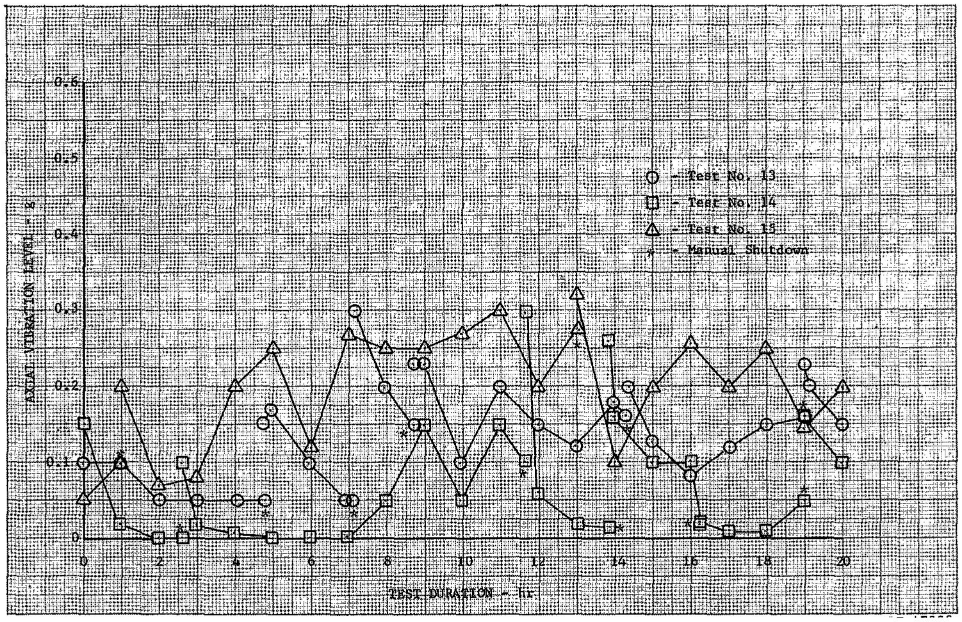


Figure V-13. Vibration Level vs Time - AISI 440C Balls and Star J Plates DF 47309

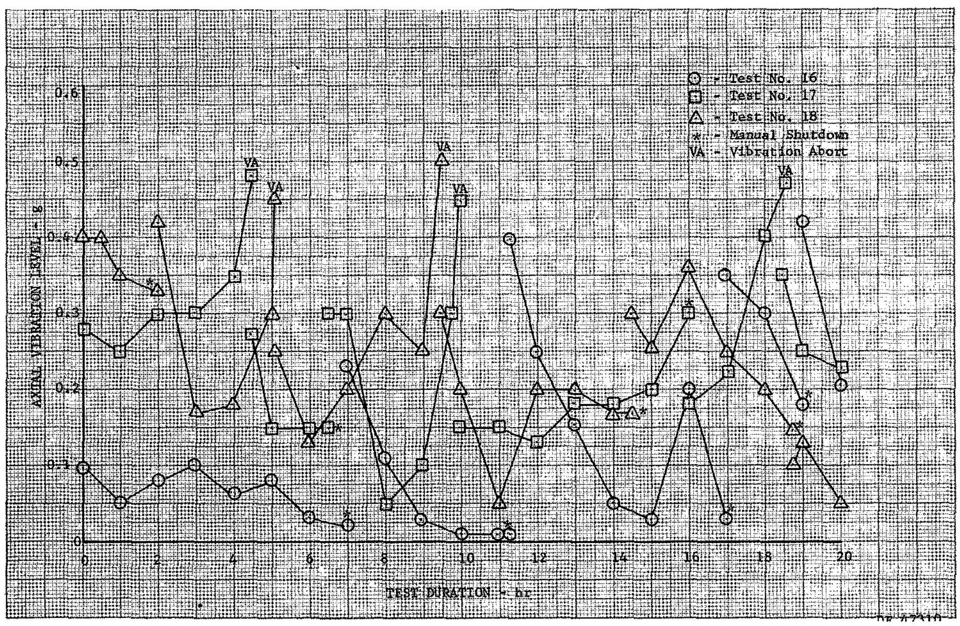


Figure V-14. Vibration Level vs Time - Star J Balls and Plates DF 47310

2. Subsurface Microstructure

Examination of the microstructure did not show any cracking due to fatigue in either the Star J or the AISI 440C materials, but cracking due to foreign matter inclusions (figure IV-4a and b) and porosity (figure V-6) were experienced.

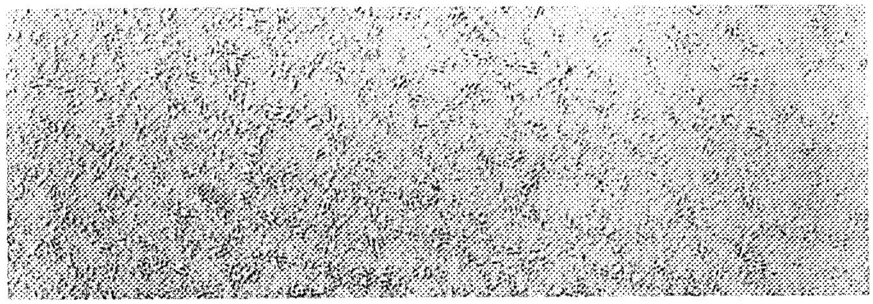
Structural characteristics of the metals were:

1. AISI 440C - Photomicrographs of the AISI 440C plates and balls show a consistent fine grain structure as illustrated by figures V-5 and V-7a, VI-4a and VI-5a, and V-7a. All of the specimens had the same general grain characteristics whether produced in large cylinders and made into sections for the plates, or produced as balls.
2. The Stellite Star J specimens taken from both flat plates and balls exhibited a wide variation in grain size and structure of the cast material. Figures V-6b and V-7b show a coarse grain with large needle shaped crystals interspersed throughout the sample. Figure V-15 reveals nonuniform grain structure within a ball varying from a fine grain at the center to a relatively coarse grain near the surface and little or no needle crystalline structure except at the ball surface region. Figure V-16 shows a fine uniform grain structure throughout the ball. The wide variation between specimens as well as within some specimens indicates that more stringent processing controls are required to provide a consistent uniform material structure, before the full potential of this material can be realized.

3. Degree of Wear

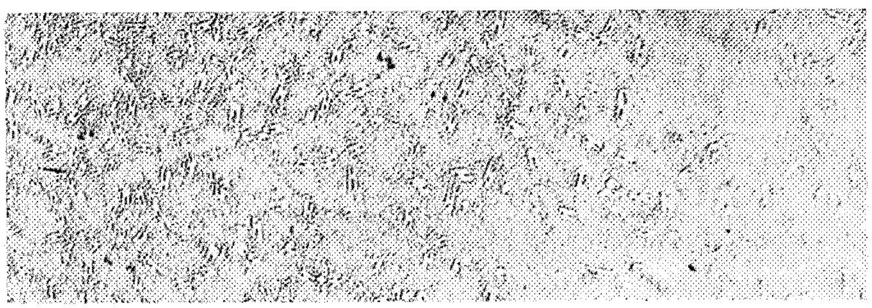
Ball wear as measured by diameter reduction and weight loss was very small for both materials tested, and no one material was rated significantly better than the other regarding this factor.

The flat plate surface wear, which was measured using the Taylor Hobson Surface Micrometer, was lowest for all AISI 440C material tests and indicates a better wear quality than that of the Star J material.



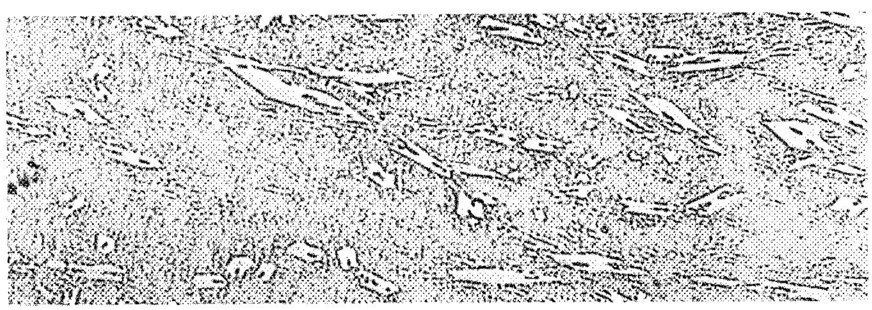
FAM 43246 (Mag: 100X)

a. Grain Size at Center of Sectioned Ball



FAM 43247 (Mag: 100X)

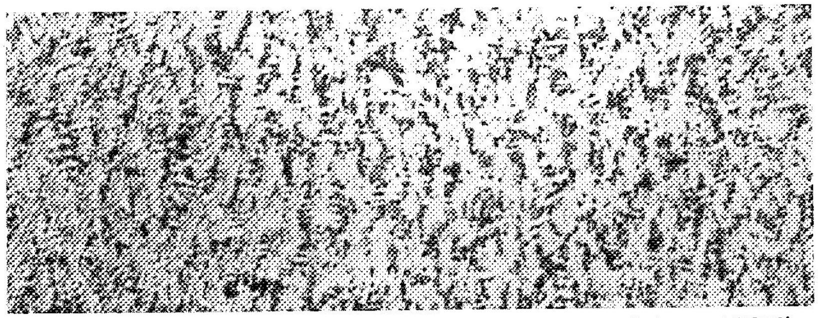
b. Grain Size Midway Between Center and Surface of Sectioned Star J Ball



FAM 43248 (Mag: 100X)

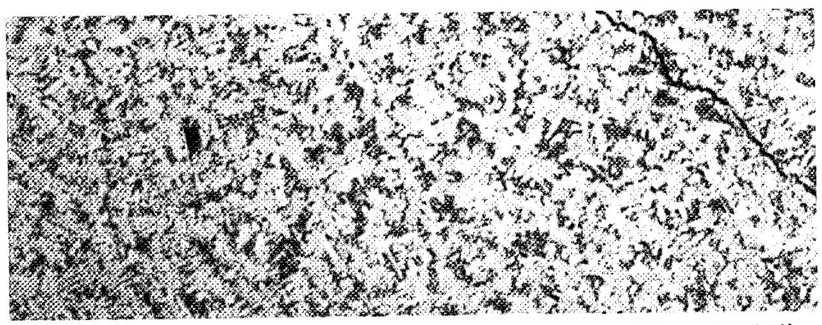
c. Grain Size Near Surface of Sectioned Star J Ball

Figure V-15. Photomicrographs of Star J Ball at Various Radial Locations Showing Variation of Grain Size. Black spots are voids in the material. FD 41130A



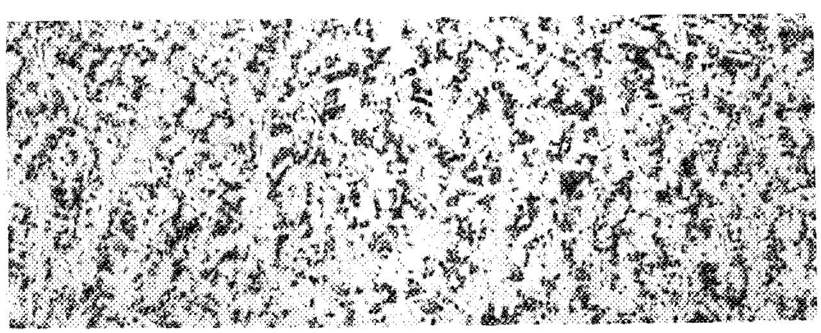
FE 102690 (Mag: 100X)

a. Grain Size at Center of Sectioned Ball



FE 102690 (Mag: 100X)

b. Grain Size Midway Between Center and Surface of Sectioned Star J Ball



FE 102690 (Mag: 100X)

c. Grain Size Near Surface of Sectioned Star J Ball

Figure V-16. Photomicrographs of Star J Ball at Various Radial Locations Showing Uniformity of Grain Size FD 45124

4. Hardness of Critical Areas

The hardness change of the test specimens did not show a pattern for either material; therefore, no significance was placed on this factor.

5. Wear of Lubricant Inserts

The average wear of Chemloy 719 inserts was lowest with AISI 440C balls and plates.

6. Vibration as a Function of Time

Because of the erratic nature of the vibration record, no conslusions on material qualities could be made using this factor.

D. LABORATORY REPORT

The Stellite Star J balls that failed in tests No. 10 and 11 in the ball-plate test rig were analyzed in the Materials Development Laboratory, FRDC. Results are presented below.

1. Test No. 10

All three of the balls that had been used in test No. 10 for 13 hours and 44 minutes had fractured, as shown in figure V-15a. Examination under the binocular microscope showed the fractures to have occurred along the grain boundaries of large needle-shaped crystals.

Electron-microscopy showed evidence of overstressing in the fracture faces.

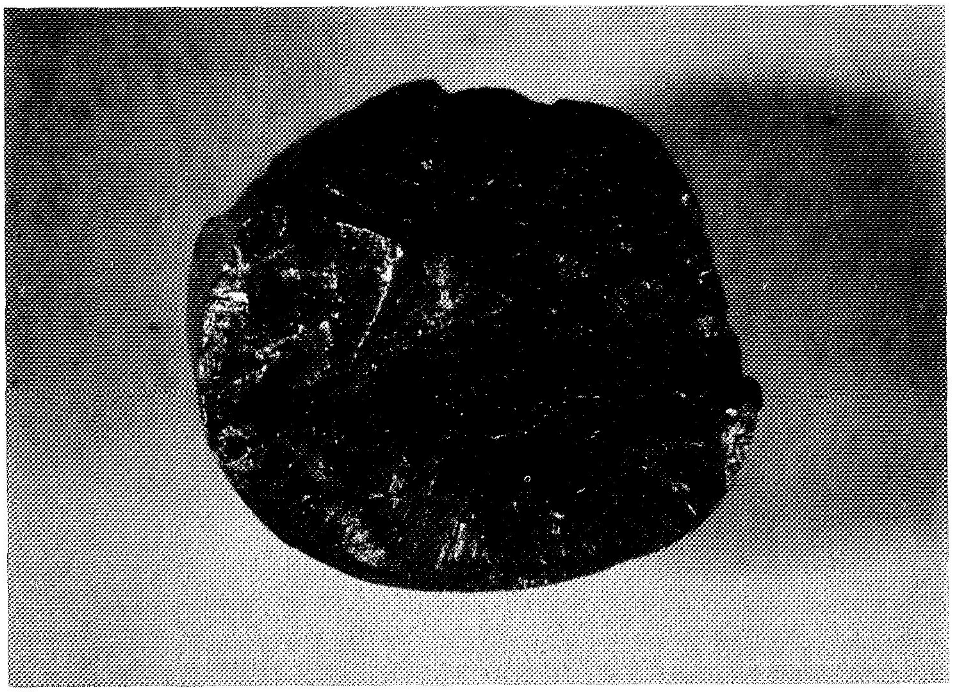
Spectrographic examination confirmed the material to be Stellite Star J.

Hardness of the balls was found to be Rockwell C 62-64 (Zwick hardness tester, 3-kg load).

The ball failure appears to have been caused by excessive loading and not by metal fatigue.

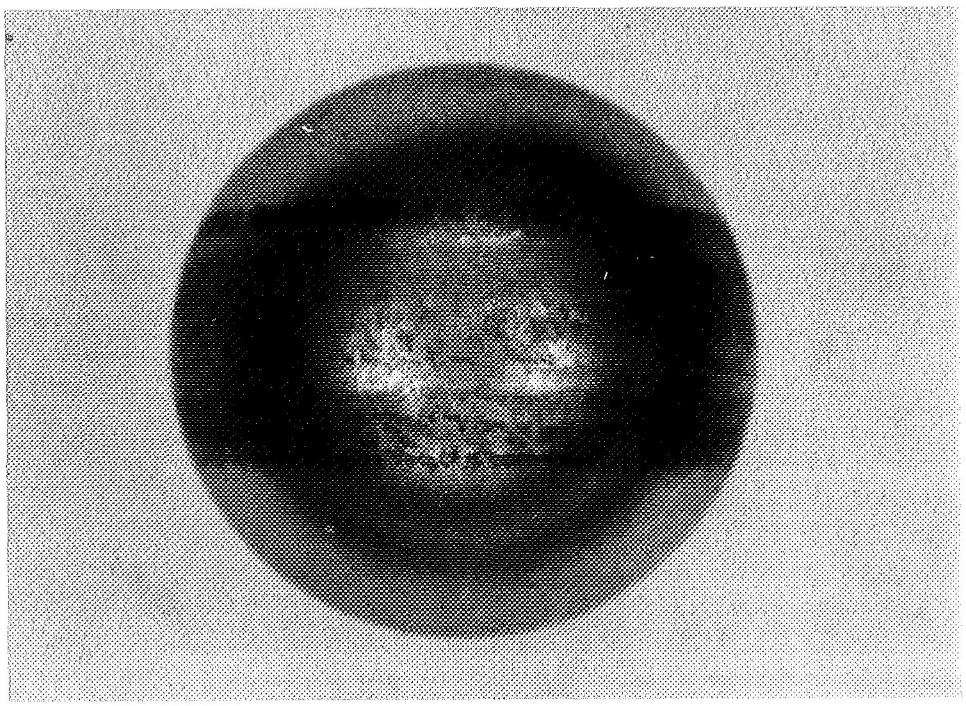
2. Test No. 11

The ball from test No. 11 (figure V-17b) exhibited pits in the contact zone. This ball was sectioned and examined by microscope (figure V-6). The photographs show the large needles and the porosity in the structure of the Star J material. Porosity appeared on the surface of the ball after testing was completed. The porosities were apparently thinly covered by metal-smearing during manufacture, and wear during testing uncovered the pits shown in figure V-17b.



(MAG: 8X)
FL 8392

Figure V-17a View of Fracture Face on Star J Ball (Exhibiting Markings that were Identified Resulting from Failure Along Boundaries of Large Needles) (Test No. 10)



(MAG: 8X)
FL 8392

Figure V-17b Overall View of Star J Ball Showing Spalling in Weak Tracks (Test No. 11)

SECTION VI
BALL AND RACE MATERIAL TESTS AND SELECTION USING SALOX M LUBRICANT MATERIAL

A. GENERAL

Under the original contract, 12 tests of material combinations of Stellite Star J and AISI 440C balls and races operating with Chemloy 719 lubricant inserts were completed. The results of these tests indicated that the Chemloy 719 wore more rapidly with Star J balls and/or plates than with the AISI 440C ball and plate material. Since wear is mainly a surface phenomena, it was theorized that minute surface asperities in the Star J material caused the higher wear rate, and that if Salox M material were used as a lubricant, these pores might be filled with the bronze particles in Salox M, thereby reducing further wear. This reasoning prompted an expansion of the test program to include ball-plate tests using Star J balls and plates with Salox M lubricant inserts.

This additional testing consisted of evaluating the performance of Star J balls and plates, and Star J balls and AISI 440C plates with Salox M lubricant inserts. Three tests of each material combination were conducted using the ball-plate test rig. All of the six tests completed 20 hours of endurance testing in liquid hydrogen without experiencing a failure. The material combination of AISI 440C balls and plates with Salox M lubricant inserts was previously tested in the lubricant screening program; therefore, it was not repeated.

Table VI-1 presents an overall evaluation of the test parameters from the Salox M tests. Tables B-19 through B-24 in Appendix B present data from the individual tests conducted in this portion of the program. Tests No. 2, 4, 5, and 9, which were conducted in the lubricant screening portion of the program, were not repeated, but the data were used in the overall evaluation in this phase of testing. Tables B-1, B-4, B-5, and B-9 present the individual data for these tests.

During the earlier testing with Chemloy 719 lubricant, the performance of Star J plates and AISI 440C balls did not appear promising due to a high wear rate on both the balls and the lubricant inserts. Therefore, during testing with Salox M, this combination of ball, plate, and lubricant was eliminated in the interest of economy.

Table VI-1. Average Wear and Weight Loss of Test Balls and Salox M Lubricant Inserts*

Material Combination	Test No.	Test Duration, hr	Average Ball Wear, in.	Average Ball Weight Loss, gm	Average Ball Weight Loss, %	Average Insert Wear, in.	Average Insert Weight Loss, gm
AISI 440C Plates	2	20	0.0000	0.002	0.06	0.064	0.094
AISI 440C Balls	4	Ball failure.					
	5	Rig failure caused test item failure.					
	9	20	0.0001	0.000	0.00	0.049	0.062
Average 2 Tests			0.0001	0.001	0.03	0.056	0.078
AISI 440C Plates	19	20	0.00027	0.0003	0.008	Side Wear	0.0192
Star J Balls	20	20	0.00028	0.0000	0.000	0.0200	0.0043
	21	20	0.00026	0.0002	0.005	0.0364	0.0192
Average 3 Tests			0.00027	0.0002	0.004	0.0282	0.0142
Star J Plates	22	20	0.00021	0.0000	0.000	0.0512	0.0493
Star J Balls	23	20	0.00026	0.0001	0.003	0.0249	0.0651
	24	20	0.00026	0.0005	0.013	0.0429	0.0433
Average 3 Tests			0.00024	0.0002	0.005	0.0396	0.0525

*The data used to compile this table can be found in tables B-2, B-4, B-5, B-9, and B-19 through B-24.

B. FACTORS CONSIDERED IN THE TEST PROGRAM AND ANALYSIS OF TEST DATA

The parameters used to assess and compare test data of the material combinations were as follows (the same as those listed in Section V):

1. Surface condition after testing
2. Subsurface microstructure in contact areas
3. Degree of wear
4. Hardness of critical areas
5. Wear of lubricant inserts
6. Vibration as a function of time.

The results of the analyses of each factor are discussed in the following paragraphs.

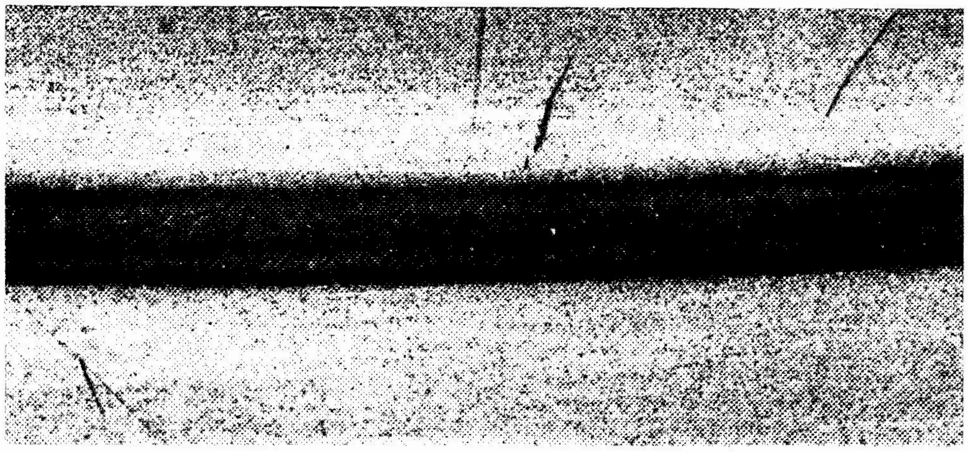
1. Surface Condition After Testing

Photomicrographs were made of the surface of one ball and the flat plate from each test. Of these, one set of photomicrographs was chosen as representative of the particular combination of materials and these are presented in figures VI-1 through VI-3.

Figure VI-1 shows photomicrographs of the surfaces of a ball and plate of AISI 440C after 20 hours of testing in liquid hydrogen with a Salox M lubricant. The dark color of the ball track on the flat plate shown is typical of that experienced in the ball-plate tests conducted during the material screening phase and is caused by the mechanical transfer of the Salox M by the balls to the flat plate.

The wear pattern shown on the ball is also typical of previous ball-plate tests conducted under this program. It indicates that the ball is rolling about a single axis, a condition that is described in Section V of this report. No wear was evident on this ball, and the surface looked almost new.

Figure VI-2 presents photomicrographs of the surfaces of a Star J ball and the AISI 440C flat plate on which it was run for 20 hours in test No. 21. Again, no surface distress was evident and the wear path was normal. The Star J ball shows two distinct paths of wear. This is believed to be due to a reorientation of the ball after opening the rig for a routine inspection during the test program. The surface of the ball shows normal wear with no distress due to fatigue.



(MAG: 8X)

Figure VI-1a. AISI 440C Flat Plate Wear Pattern Using Salox M Lubricant (Test No. 2) FD 19441

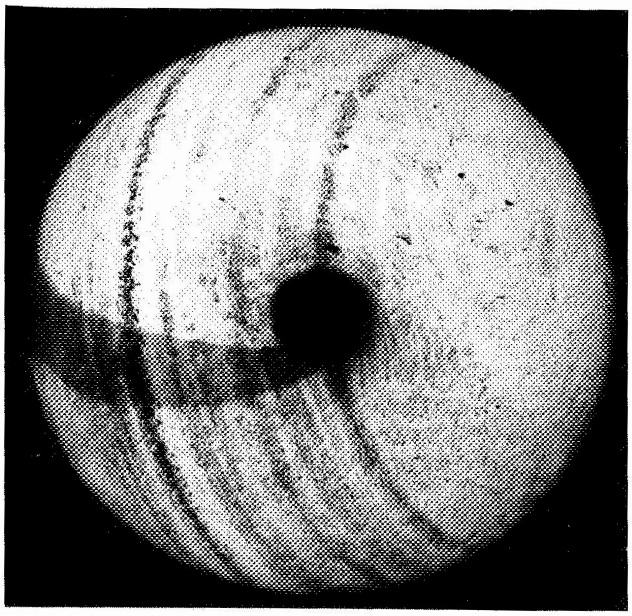


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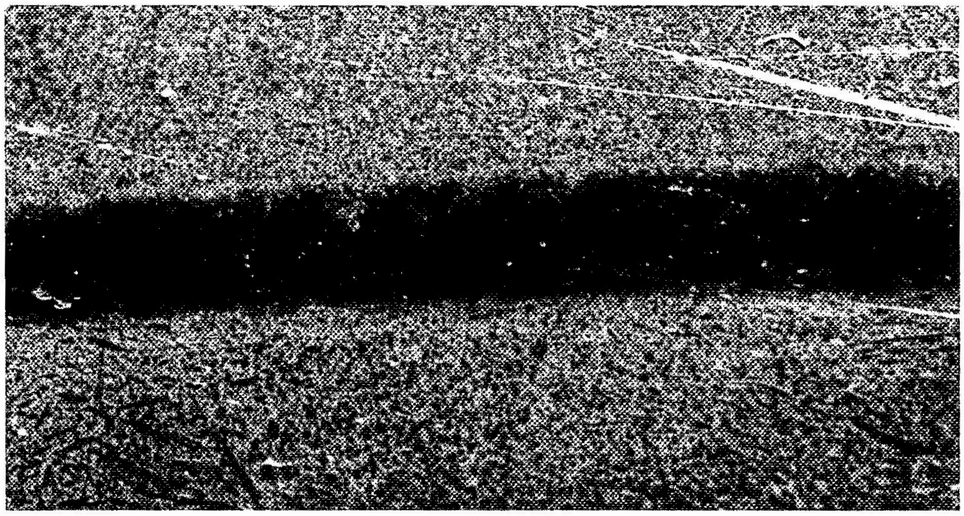
Figure VI-1b. AISI 440C Ball Wear Pattern Using Salox M Lubricant (Test No. 2) FD 19441



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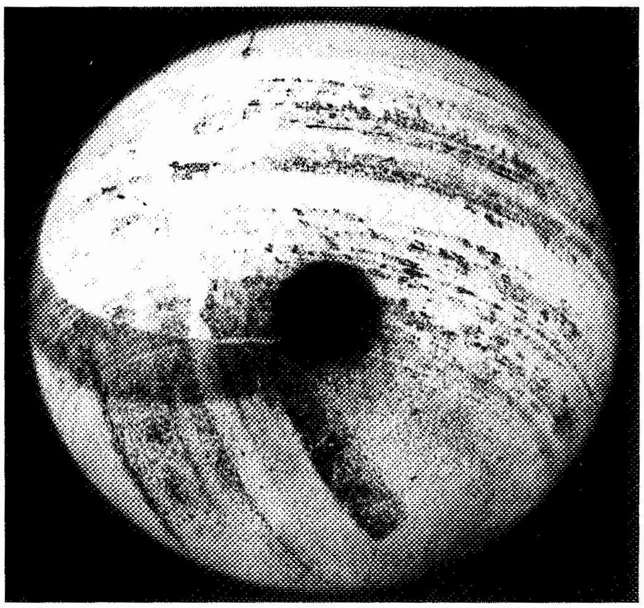
FD 19442

Figure VI-2a. AISI 440C Ball Wear Pattern Using Salox M Lubricant (Test No. 2)



(MAG: 8X)
FD 19442

Figure VI-2b. Star J Ball Wear Pattern Using Salox M Lubricant (Test No. 2)

Figure VI-3 presents photomicrographs of the surfaces of a ball and plate made of Star J that was tested for 20 hours during test No. 23. The flat plate shows normal wear with no surface distress. The Star J ball does not show the usual distinct wear paths, indicating the ball was spinning in this test.

Inspection of the ball and plate surface conditions, after equivalent tests were made with Salox M and various ball and plate material combinations, showed no one outstanding material combination. On this basis Star J and AISI 440C are equally good bearing race and ball materials when lubricated by Salox M.

2. Subsurface Microstructure in Contact Areas

A post-test subsurface microscopic examination was made on all ball and plate test samples both before and after etching. The balls and plates were sectioned to reveal the subsurface zone. The subsurface zone is approximately 0.020-in. deep, and is the area where bearing fatigue failures normally originate. No evidence of subsurface distress or cracks due to fatigue was noted in any of these samples. Typical photomicrographs of the edges of etched samples are presented. The dark zone shown at the edge of the photographs is the plastic used to mount the samples. Figure VI-4 shows AISI 440C and Star J ball sections magnified by 100X. The grain structures are representative of all of the balls tested during this program.

Sections of AISI 440C and Stellite Star J plates are shown in figure VI-5. The coarse dendritic structure of the Star J is in contrast to the small grain structure of the AISI 440C material. Because of the relatively small number of tests and the lack of consistency of the Star J structure, it is not possible to make an absolute judgment on its merit as a bearing material. Owing to the structural inconsistency exhibited unless quality control can be improved, the material offers less promise than the AISI 440C.

3. Degree of Wear

Evaluation of the wear experienced by the test specimens was made using the methods described in Section IV of this report and consisted of dimensional and weight change measurements.

(MAG: 8X)

Figure VI-3a. Star J Flat Plate Wear Pattern Using Salox M Lubricant (Test No. 24) FD 19443

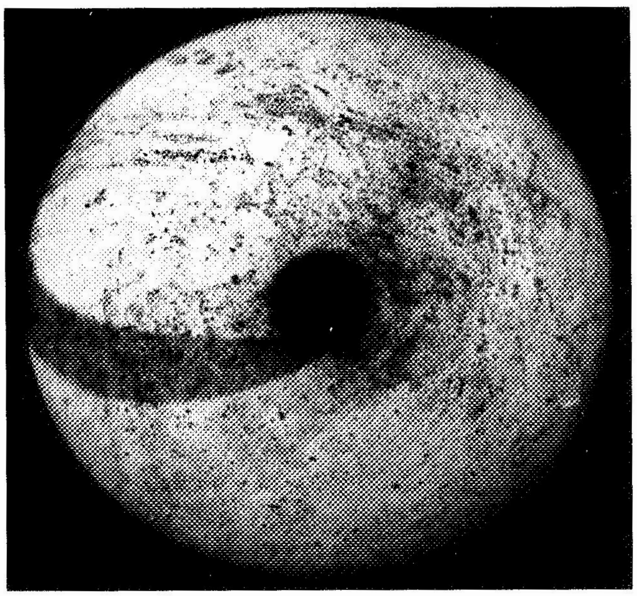


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Figure VI-3b. Star J Ball Wear Pattern Using Salox M Lubricant (Test No. 24) FD 19443

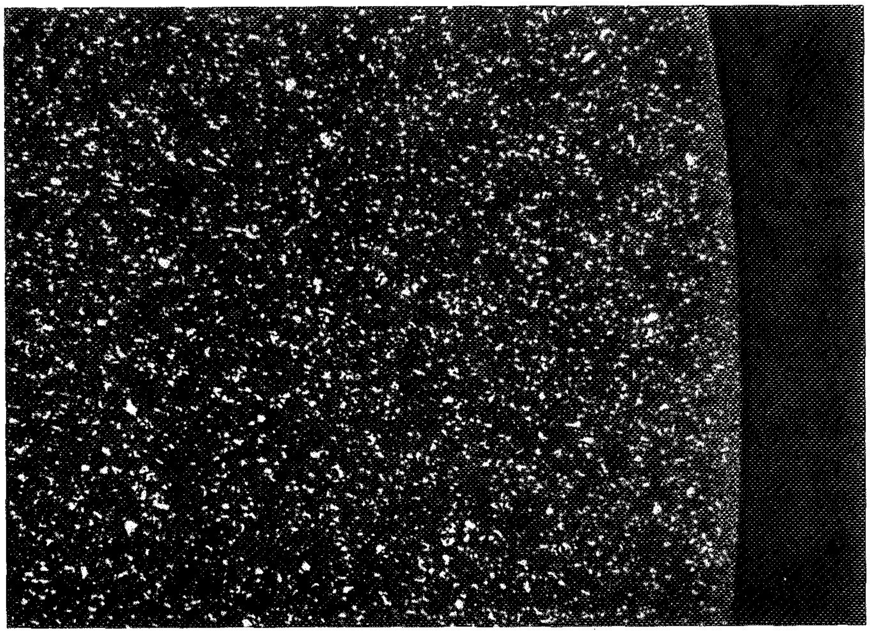

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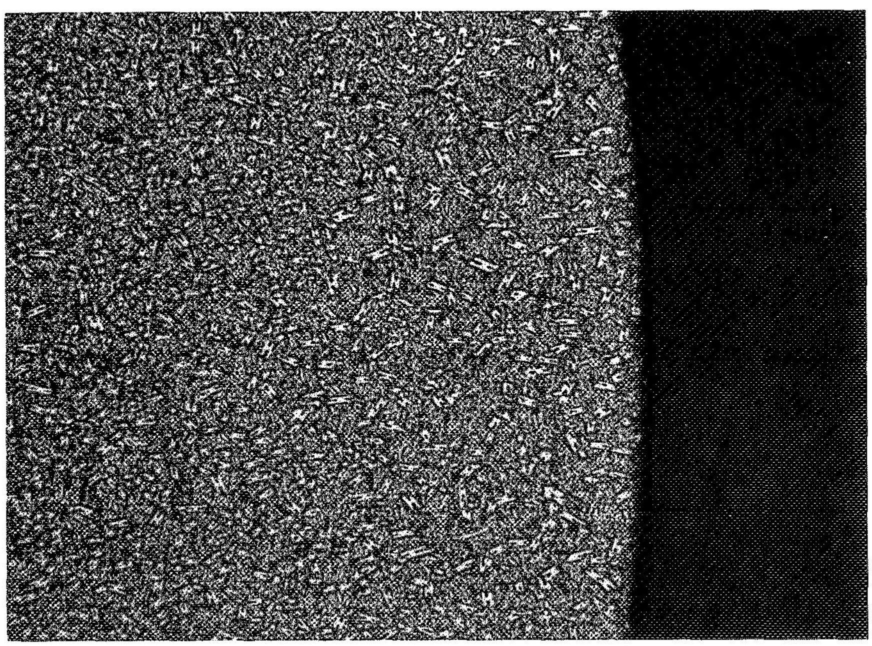
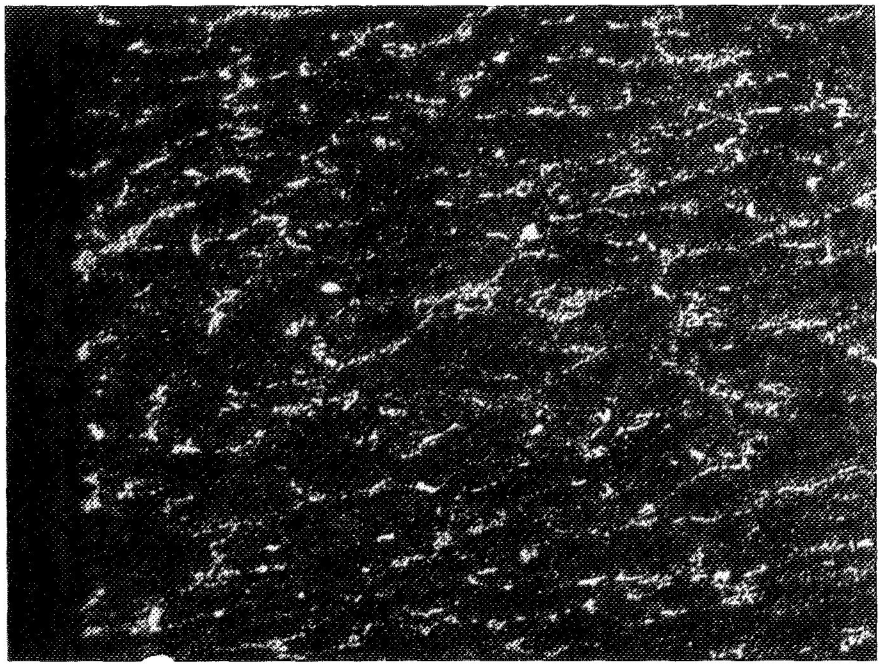
Figure VI-4a. Characteristic Microstructure: AISI 440C Ball Tested With Salox M Lubricant FD 19470



(MAG: 100X)

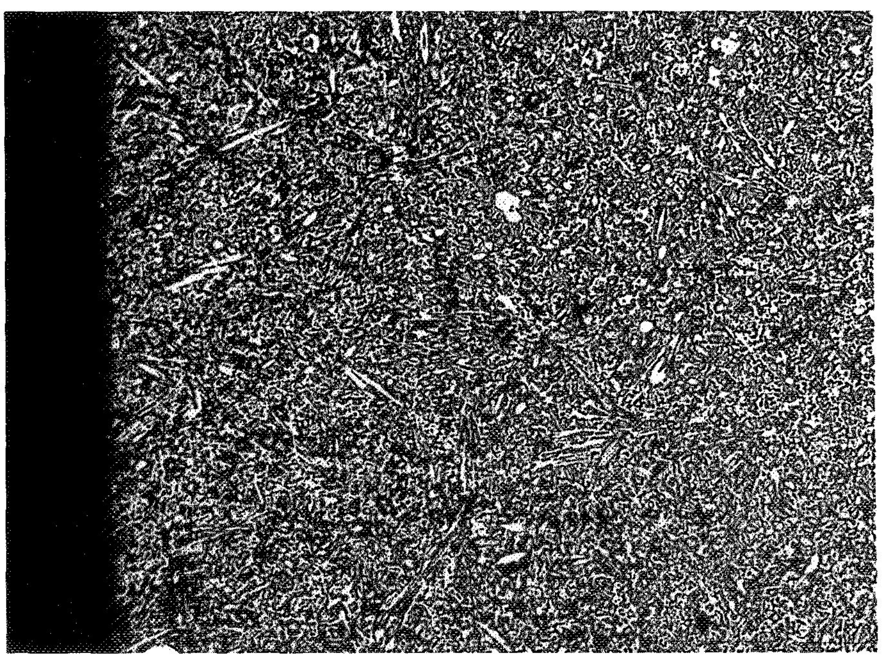
Figure VI-4b. Characteristic Microstructure: Star J Ball Tested With Salox M Lubricant FD 19470



(MAG: 100X)

Figure VI-5a. Characteristic Microstructure: AISI 440C Tested With Salox M Lubricant

FD 19471



(MAG: 100X)

Figure VI-5b. Characteristic Microstructure: Star J Plate Tested With Salox M Lubricant

FD 19471

a. Test Balls

(1) Ball Diameter

As indicated in tables B-2, B-3, B-4 and B-9 of Appendix B, ball diameter was only measured to four significant figures in the tests of the AISI 440C balls and plates. In the later tests reported in tables B-19 through B-24, ball diameter was measured to five significant figures. Comparison of these data in table VI-1 indicates that the AISI 440C balls rolling on AISI 440C plates give the smallest diameter change, although there is some uncertainty in this because of the fewer significant figures in the measurement. The other two material combinations experienced more than twice as much ball wear, and they were approximately equal within the accuracy of measurement.

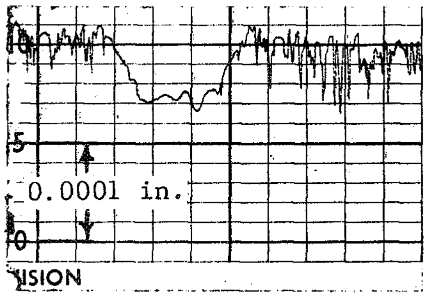
(2) Ball Weight

As may be seen in table VI-1, the average percent weight change is very small for all materials, ranging from 0.004 to 0.03%, The least weight change was measured on the Star J balls, and the effect of plate material was not significant. It is observed that the AISI 440C balls rolling on AISI 440C plates experienced the greatest weight loss of the ball and lubricant materials tested, but the least ball diameter change. No reasonable explanation for this has been found. One possibility is unequal amounts of Salox M lubricant adhering to the balls, but cleaning the balls in nitric acid (one from each test) did not change the weight within the accuracy of the measurement.

It is concluded that on the basis of ball wear neither Star J nor AISI 440C holds a significant advantage over the other.

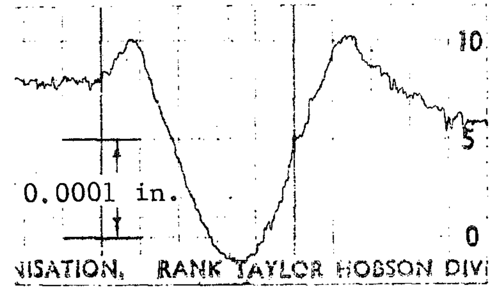
b. Test Plates

Analysis of plate wear was conducted considering the flat plates only, since the loading on the surface was higher and surface wear was more easily measured than on the grooved plates. Surface wear measurements were made using a Taylor Hobson Surface Micrometer, which traces the surface irregularities and presents the magnified trace on a tape. These traces are presented in figures VI-6 and VI-7. The traces show wear track depth ranging from 0.00003 to 0.00018 in. below the original surface with a small pile-up of material on the edge of the track in some tests. The average wear track depth below the original surface is in the following summary.



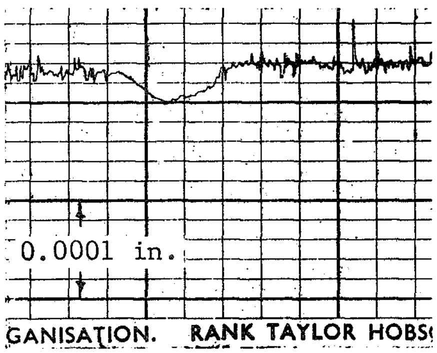
Test No. 2, 20 Hour^r

The flat plate surface wear of tests No. 4 and No. 5 was not measured due to failures occurring during the test runs.

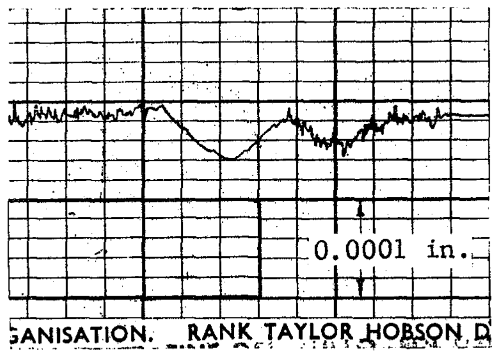


Test No. 9, 20 Hours

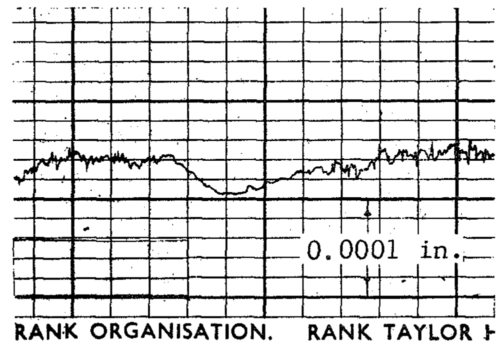
AISI 440C Plates and AISI 440C Balls - Salox M Lubricant Inserts



Test No. 19, 20 Hours



Test No. 20, 20 Hours

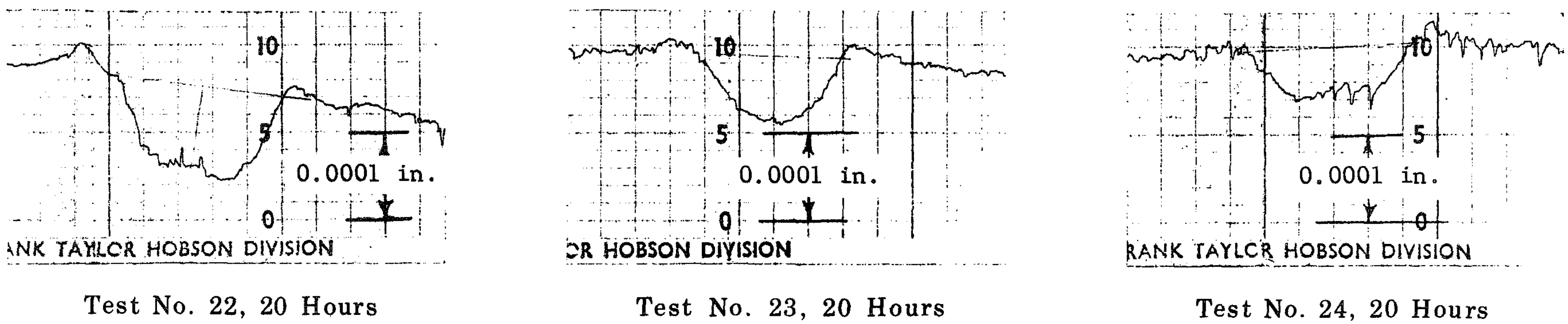


Test No. 21, 20 Hours

AISI 440C Plates and Star J Balls - Salox M Lubricant Inserts

Figure VI-6. Flat Plate Wear Groove Depth, Tests No. 2, 9, 19, 20, and 21

FD 19468A



Star J Plates and Star J Balls - Salox M Lubricant Inserts

Figure VI-7. Flat Plate Wear Groove Depth, Tests No. 22, 23, and 24

FD 19469A

Plate Material	Ball Material	Average Wear Track Depth, Inch
AISI 440C	AISI 440C	0.00012
AISI 440C	Star J	0.00003
Star J	Star J	0.00008

Comparison of the data from these tests shows a lower flat plate wear rate for the combination of AISI 440C plates and Star J balls than for the other combinations tested when lubricated by Salox M.

4. Hardness of Critical Areas

a. Test Plates

To investigate a possible change of hardness due to cold working of the flat plate surfaces by the action of the balls, the surface hardness of the sample plates was checked before and after testing as described in Section IV.

The data on table VI-2 indicate an average hardness increase of about 4 points Rockwell C in the ball paths of both the AISI 440C and the Star J flat plates. The apparent decrease in hardness shown in table VI-2 for some of the grooved plates is not considered significant because the post-test hardness was not measured on the wear path where work hardening would be expected.

b. Test Balls

The data indicate an average increase in ball hardness of 1 to 2 points on the Rockwell C scale with no apparent advantage for either material.

5. Wear on Lubricant Inserts

As with the balls, two methods of measuring wear rate were used in the tests on the Salox M lubricant samples: direct measurement of the ID of the ball pocket, and weight of the lubricant insert before and after testing. The photograph in figure VI-8 of a typical insert shows the wear experienced during a 20-hour test. Individual insert data are shown in tables B-19 through B-24, and B-2, B-4, B-5, and B-9 of Appendix B and average data for the tests are presented in table VI-1. Analysis of these data shows a lower rate of wear for the inserts when tested with Star J balls and AISI 440C plates.

Table VI-2. Average Rockwell C Hardness of Test Balls and Plates

Material Combination	Test No.	Pretest	Flat Plate Post-Test Beside Track	Flat Plate Post-Test in Track	Grooved Plate Pretest	Grooved Plate Post-Test*	Balls Pretest**	Balls Post-Test*
AISI 440C Plates	2	54	57	60	54	54	56	57
AISI 440C Balls	4	Tests No. 4 and 5 failed as reported in Quarterly Report No. 2, PWA FR-1750.						
	5							
	9	54	57	60	54	55	56	57
Average 2 Tests		54	57	60	54	55	56	57
AISI 440C Plates	19	56	58	61	56	55	57	59
Star J Balls	20	55	55	56	56	53	57	59
	21	55	56	59	55	53	57	58
Average 3 Tests		55	56	59	56	54	57	59
Star J Plates	22	57	60	62	58	57	57	60
Star J Balls	23	58	57	62	57	56	57	58
	24	58	58	62	57	56	57	60
Average 3 Tests		58	58	62	57	56	57	59

* Hardness data were taken from sectioned balls and grooved plate.

** Minimum hardness as certified by the vendor. Pretest hardness could not actually be determined from balls used in the test without destroying the surface finish and sphericity of the ball.

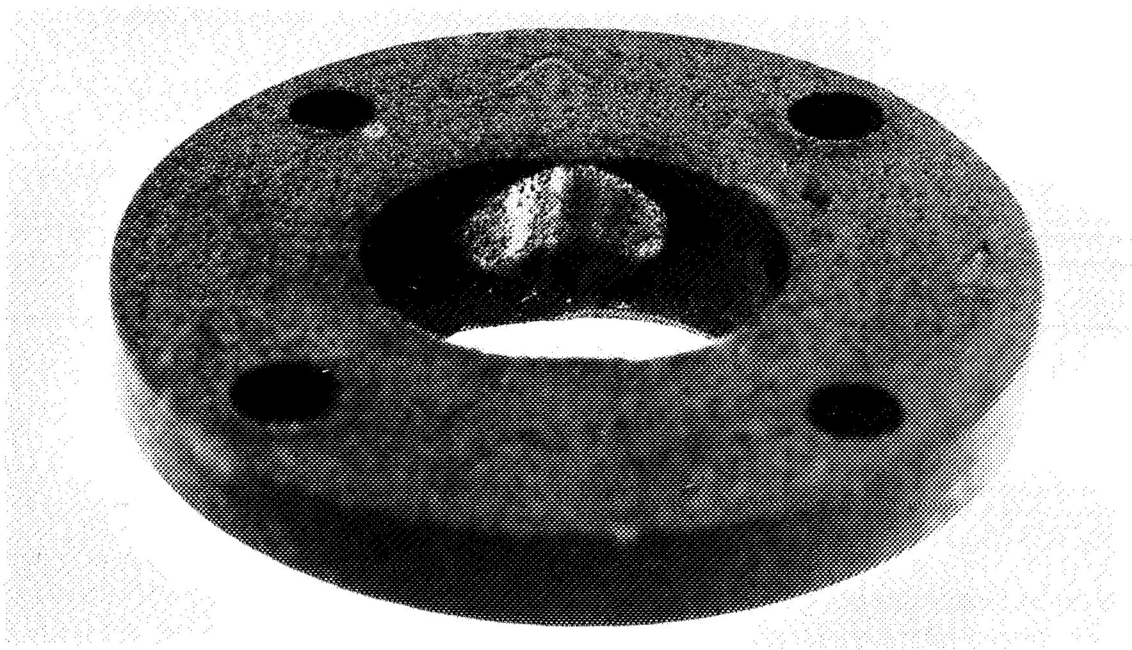


Figure VI-8. Salox M Insert After 20-hr Test With AISI 440C Plates and Star J Balls (Test No. 21) FE 66323

6. Vibration as a Function of Time

Plots of test rig axial vibration, as measured by an axial accelerometer on the loading end of the tester, are presented in figures VI-9 through VI-11. As can be seen the data are erratic and the vibration level both increases and decreases with time over the period of test. Except where failure of a component is occurring, as in test No. 4 on figure VI-9, the level of vibration is believed to be due to particles of lubricant being deposited on the plate on the ball track and the subsequent wearing and smoothing of these lubricant particles as the balls roll over them. In general, the vibration level of the Star J balls on AISI 440C plates (see figure VI-10) is lower than the other two material combinations tested.

C. CONCLUSIONS

From the analysis of the six parameters just presented, the following conclusions were reached for the ball-plate testing using Salox M for the lubricant insert material.

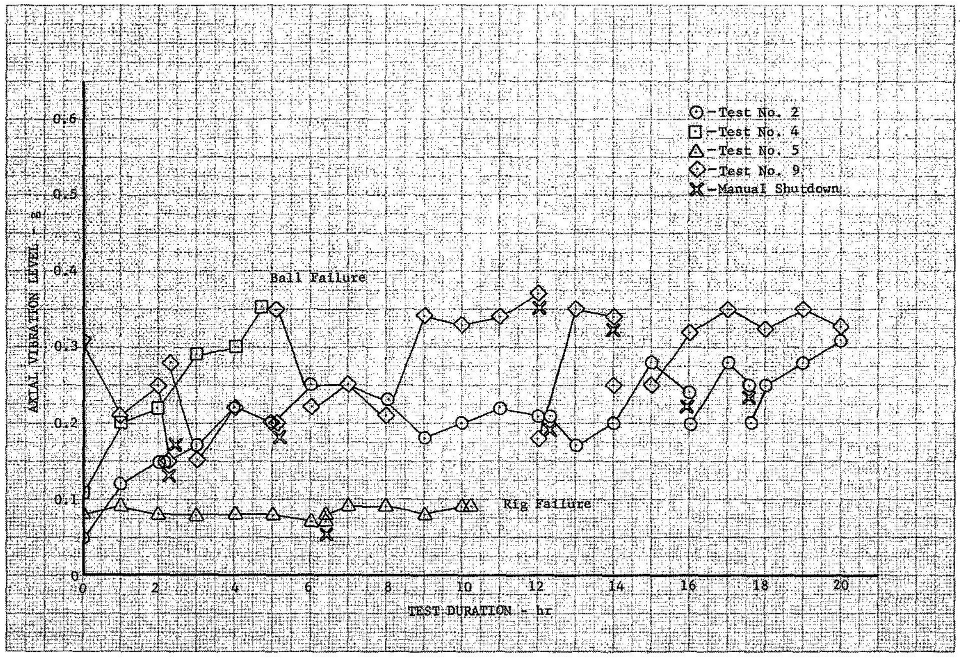


Figure VI-9. Vibration Level vs Time, AISI 440C Balls and Plates DF 53898

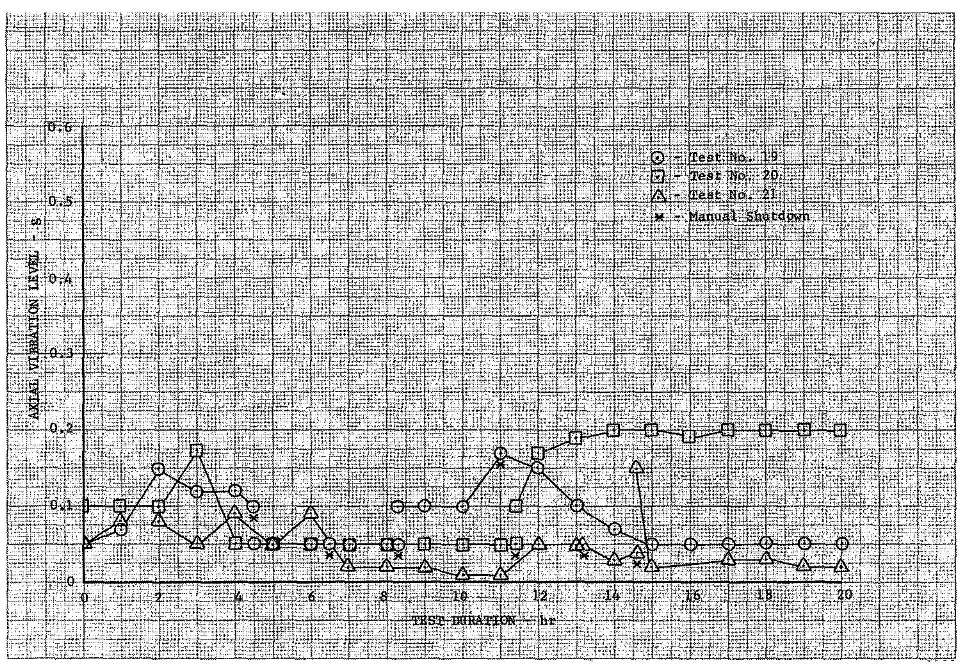


Figure VI-10. Vibration Level vs Time, Star J Balls and AISI 440C Plates DF 53899

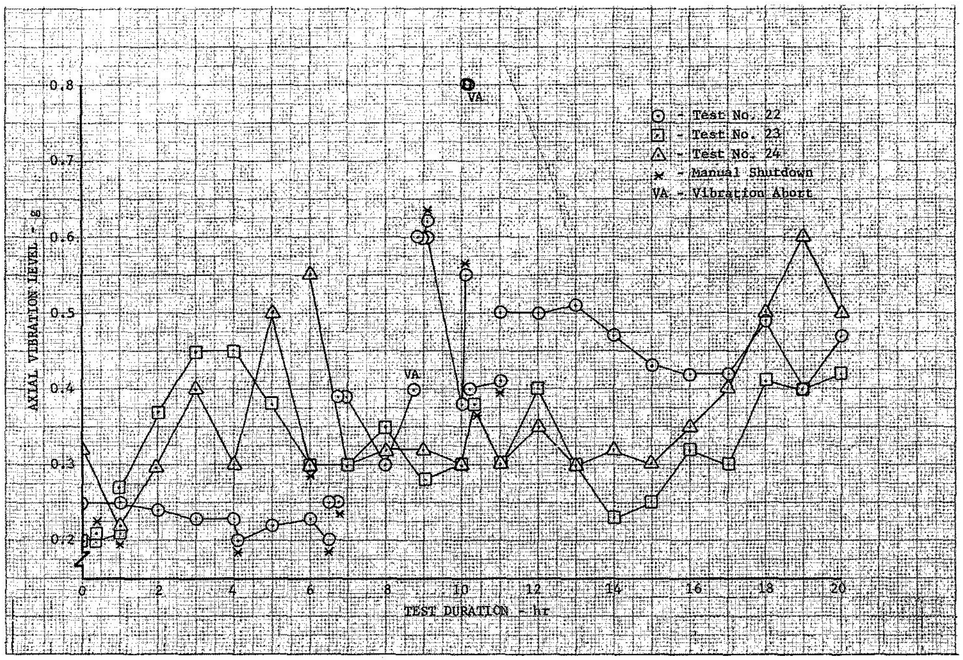


Figure VI-11. Vibration Level vs Time, Star J Balls and Plates   DF 53900

1. Surface Condition

On the basis of the general appearance of the surface of the test items after test, Star J and AISI 440C are rated equally good as ball and race materials.

2. Subsurface Microstructure

Examination of the subsurface microstructure of the Star J and AISI 440C balls and plates did not reveal any fatigue cracks. However, there is a significant difference in grain size, with the Star J balls having a rather coarse structure as compared to the finer-grain AISI 440C balls. The Star J structure is also erratic, as shown by figures V-6 and V-15.

3. Degree of Wear

Ball wear as measured by diameter reduction and weight loss was very small for all materials tested, and no one material is rated significantly better than the other as measured by this factor.

4. Hardness of Critical Areas

A change of hardness of approximately an equal amount was experienced in both AISI 440C and Star J balls and plates. There is no apparent advantage in the use of either material based on this criterion.

5. Wear of Lubricant Inserts

The lowest wear of the lubricant inserts was experienced with Star J balls run on AISI 440C plates.

6. Vibration as a Function of Time

The average vibration level was lowest during the testing of AISI 440C plates and Star J balls.

As a result of the analysis presented in this section it has been recommended that the six additional bearings to be procured and tested be fabricated with AISI 440C races, Stellite Star J balls, and a Salox M cage lubricant.

The testing of these bearings will be reported in Part II of the final report.

SECTION VII
DISCUSSION OF THE BALL-PLATE APPARATUS TEST RESULTS

A. COMPARISON OF SALOX M AND CHEMLOY 719 AS A LUBRICANT MATERIAL

A wide variety of parameters were considered in the evaluation of these materials for use in bearings. These parameters included:

1. Ball wear (dimensional)
2. Percentage of weight loss of balls
3. Dimensional wear of lubricant inserts
4. Weight of loss of inserts
5. Ball track depth in flat plate.

Each of these items will be discussed separately in subsequent paragraphs.

Table VII-1 was prepared to aid in correlation of the performance of the materials for each of these parameters; figures VII-1 and VII-2 further clarify the data. Use of these illustrations provides a means of directly comparing the two lubricant materials under the conditions tested. In the preparation of table VII-1, the weight loss of the test balls in grams was omitted in favor of the more meaningful percentage weight loss factor.

When consideration is given to the relatively short bearing life requirements being considered it is apparent that only sufficient lubricant need be included to support that limited bearing operating life. This fact makes the major factor in lubricant performance the wear on the balls and races.

1. Comparison of Lubricant Performance Parameters

a. Ball Wear (Dimensional)

With AISI 440C balls and plates no advantage was indicated for either Salox M or Chemloy 719.

When AISI 440C plates and Star J balls were tested, the ball wear appears least when lubricated by Chemloy 719, but when the apparent wear rate is extrapolated linearly to 20 hours from the actual 11 hours of testing, the wear is approximately equal to that of Salox M. Thus, no real preference can be stated.

Ball wear with Salox M lubricated Star J balls and plates was only half that with Chemloy lubricant.

Table VII-1. Comparison of the Average Wear and Weight Loss of the Ball-Plate Apparatus Test Specimens - Salox M and Chemloy 719 Lubricant Materials

Material Combination and Test No.	Test Duration, hr	Average Ball Wear, in.		Average Ball Weight Loss, %		Average Insert Wear, in.		Average Insert Weight Loss, g		Flat Plate Wear Track Depth, in.		Indicated Optimum Lubricant
		Salox M	Chemloy 719	Salox M	Chemloy 719	Salox M	Chemloy 719	Salox M	Chemloy 719	Salox M	Chemloy 719	
AISI-440C Plates AISI-440C Balls												
2	20	0.0000		0.06		0.064		0.094		0.00007		
4	4.83	(1)		(1)		(1)		(1)		(1)		
5	10.45	(2)		(2)		(2)		(2)		(2)		
9	20	0.0001		0.00		0.049		0.062		0.00016		Chemloy 719
6	17		0.0001		0.04		0.058		0.041		0.00003	
7	19.93		0.0002		0.08		0.039		0.008		0.00002	
8	20		0.0001		0.07		0.048		0.017		0.00004	
Average		0.0001	0.0001	0.03	0.06	0.056	0.048	0.078	0.022	0.00012	0.00003	
AISI-440C Plates Star J Balls												
19	20	0.00027		0.008		(3)		0.0192		0.00003		
20	20	0.00028		0.000		0.0200		0.0043		0.00004		
21	20	0.00026		0.005		0.0364		0.0192		0.00003		Salox M
10	14		(1)		(1)		(1)		(1)		(1)	
11	11.5		0.00017		0.004		0.1038		0.1703		(1)	
12	20		0.00013		0.011		Worn Through		Worn Through		0.00006	
Average		0.00027	0.00015	0.004	0.008	0.0282	0.1038		0.1703	0.00003	0.00006	
Star J Plates Star J Balls												
22	20	0.00021		0.000		0.0512		0.0493		0.00010		
23	20	0.00026		0.003		0.0249		0.0651		0.00008		
24	20	0.00026		0.013		0.0429		0.0433		0.00005		Salox M
16	20		0.00080		0.119		Worn Through		Worn Through		0.00022	
17	20		0.00007		0.013		0.0170		0.0013		0.00013	
18	20		0.00083		0.070		0.0542		0.0429		0.00017	
Average		0.00024	0.00057	0.005	0.067	0.0396	0.0356	0.0525	0.0221	0.00008	0.00017	
Indicated Optimum Ball and Plate Material		AISI-440C Plates and Balls	AISI-440C Plates and Balls	AISI-440C Plates and Star J Balls	AISI-440C Plates and Star J Balls	AISI-440C Plates and Star J Balls	Star J Plates and Balls	AISI-440C Plates and Star J Balls	AISI-440C Plates and Balls Equal to Star J Plates and Balls	AISI-440C Plates and Star J Balls	AISI-440C Plates and Balls	

Note: Data used to compile this table can be found in tables V-1 and VI-1.
(1) Ball failure
(2) Test apparatus failure
(3) Installed incorrectly; wear on the side of insert pocket.

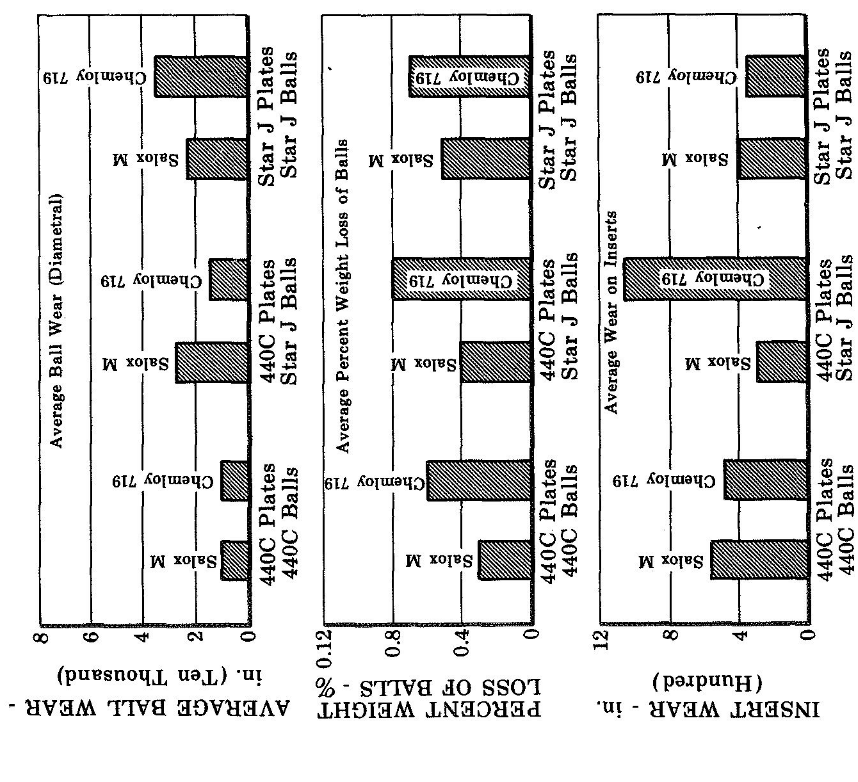


Figure VII-1. Comparative Wear Rates of Samples Tested FD 22978

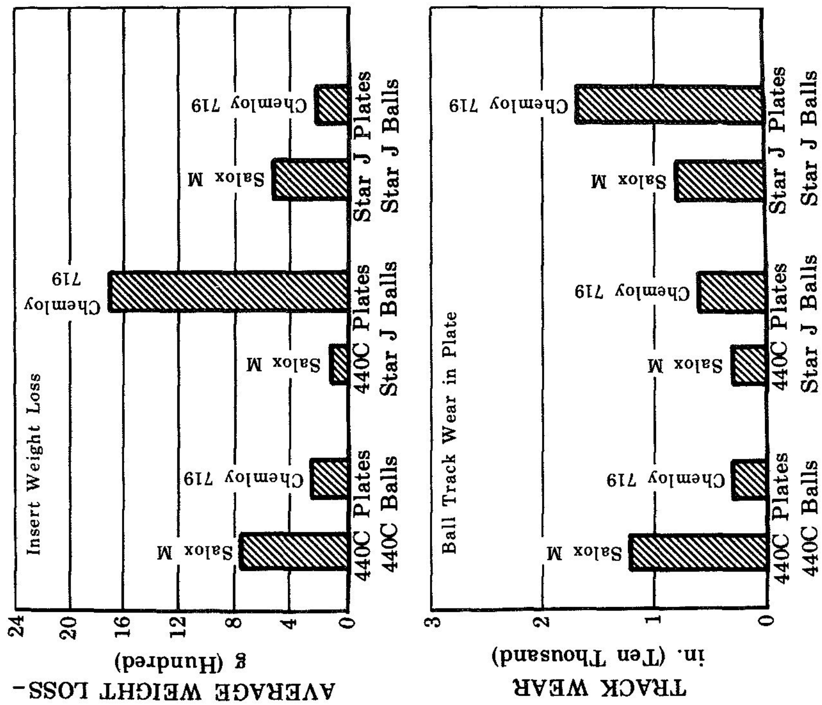


Figure VII-2. Comparative Wear Rates of Samples Tested FD 22979

No clear-cut pattern of lubricant superiority appears from this comparison, both exhibiting approximately equal performance.

b. Percentage Weight Loss of Balls

Consideration of this parameter shows a superiority of the Salox M for all combinations of balls and plates tested in this program.

c. Dimensional Wear of Lubricant Inserts

As revealed by the initial testing in the program, the Chemloy 719 appears to offer a slightly lower wear rate than Salox M when tested with AISI 440C balls and plates.

Subsequent testing with Star J balls and AISI 440C plates and Star J balls and plates show two tests in which the Chemloy 719 failed by wear-out. No explanation has been found for the high wear experienced in two of the nine tests. The more consistent performance of the Salox M makes it appear to be more tolerant to possible variations in operating conditions; therefore, Salox M is considered the more reliable lubricant when tested with balls or plates made from Star J.

d. Weight Loss of Lubricant Inserts

When the weight loss of the lubricant inserts is considered, the Chemloy 719 material shows a smaller loss except when tested with Star J balls and AISI 440C plates. (Chemloy 719 is 25% less dense than Salox M.)

As discussed under Dimensional Wear above, the Salox M shows a more consistent performance, and the fact that the wear with Salox M is slightly higher only indicates the possibility of more transfer of lubricants to the bearing elements.

Due to the more consistent performance of the Salox M, it is rated slightly better based on lubricant weight loss.

e. Ball Track Depth in Flat Plate

The flat plate wear, as measured by the surface micrometer, using the Chemloy 719 lubricant was lowest in only one set of tests, that of AISI 440C balls and plates.

The depth of the wear path for all other combinations of ball and plate materials indicates that the Salox M lubricant produced about one-half the wear that was measured with comparable tests with Chemloy 719. This indicates a superiority for Salox M when used with combinations of Star J.

f. Conclusion

The general conclusion that can be drawn from the above is that both lubricants are adequate; however, when AISI 440C is used for the balls and plates, the Chemloy 719 appears to be slightly more effective than Salox M. When Star J balls are used with either AISI 440C or Star J plates, the Salox M appears to be the better lubricant.

B. COMPARISON OF THE STELLITE STAR J AND AISI 440C AS BALL AND RACE MATERIALS

1. Averages of Wear Data

Arithmetic averages were computed for the wear on Star J and AISI 440C balls and plates, without regard to the lubricant used. These arithmetic averages are presented in table VII-2 and again show that Star J appears to be poor for wear resistance as races, but is superior to AISI 440C for balls.

2. Conclusions

The conclusions reached on the basis of these data are as follows:

1. AISI 440C is the preferred material for use in bearing races.
2. The Star J and AISI 440C materials both have merit for use as a bearing ball material and a decision as to which is best appears to be dependent upon the bearing cage lubricant to be used.

The 110-mm bearings made from these preferred material combinations are to be tested to confirm their usefulness. These tests will be reported in Part II of this final report.

Table VII-2. Overall Averages of Wear Data

Material Combination	Average Wear from Both the Chemloy 719 and Salox M Tests: Ball Wear, in.	Plate Wear, in.
AISI 440C Balls AISI 440C Plates	0.00010	0.00008
Star J Balls AISI 440C Plates	0.00021	0.00005
Star J Balls Star J Plates	0.00041	0.00013

SECTION VIII
BIBLIOGRAPHY

1. "Research and Development of Materials for Use as Lubricants in a Liquid Hydrogen Environment," PWA FR-986, NAS8-11537, 18 June 1964.

2. "Research and Development of Materials for Use as Lubricants," PWA FR-1602, Phase II Report, NAS8-11537.

APPENDIX A
BALL-PLATE TEST SPECIMEN DESIGN

The requirements set forth in the contract specify that the ball-plate testing must simulate as closely as possible the conditions that would exist in a 110-mm ball bearing operating in liquid hydrogen at DN values to 2.5 x 10^6 with 20,000 pounds of axial load.

To determine the operating values of Hertzian stress, spin/roll ratio and ball velocities, Pratt & Whitney Aircraft utilized a mathematical model that predicts the ball bearing internal dynamics for a broad combination of speeds and thrust loads. This method is based on both theoretical and experimental studies conducted with cryogenically cooled ball bearings. The 110-mm bearing design parameters derived from this program are shown in table A-1 and were used as the basis of the ball-plate test specimen design.

Since the specified Hertzian stress level, amount of spin in the ball-race contact zone, and the cage-to-ball rubbing velocity must be simulated as closely as possible in the ball-plate test apparatus, a study was made to determine the effect of varying the ball size on the accuracy of simulation. This was done because of the disparity in size of the 0.375-diameter balls normally used in the ball-plate test apparatus compared to the 0.719-diameter balls used in the 110-mm bearings to be tested. The study included considerations of ball size, material properties, spin-roll ratio, Hertz stress, and cage-to-ball rubbing velocity.

Figure A-1 shows a comparison of ball size and spin power generation. The spin power generation of the ball-plate apparatus is an order of magnitude lower than that computed for the 110-mm bearing. Because of the geometry of the ball-plate rig, the simulation of spin power cannot be improved by any reasonable increase in ball size.

Figure A-2 shows that the depth to the maximum shear stress increases with ball size. For a true simulation of this parameter in the ball-plate apparatus an unreasonably large size ball would be required; therefore, this parameter was not simulated well by the ball-plate rig.

Figure A-2 also shows that a great increase in ball size would increase the total thrust required, this would overload the rig ball bearings and result in short life and unreliable operation. Therefore, no change in ball size was made for the ball-plate tests.

The cage rubbing velocity is a function of rig radius and rotational speed only. The rubbing velocity expected in the actual 110-mm bearing is well within the capability of the ball-plate rig.

The other important parameters that were considered in the design of the ball-plate specimens were all held constant at the levels expected in the 110-mm ball bearing and can be simulated with no difficulty in the ball-plate rig.

The resultant design particulars are shown in table A-2, and are illustrated in figure A-3.

Table A-1. 110-mm Bearing Test Conditions

DN Value	2.5×10^6 mm-rpm
Hertzian Stress	315,000 psi*
Spin/Roll Velocity Ratio	0.258
Cage-to-Ball Rubbing Velocity	274 ft/sec

*The Hertzian stress value shown is based on the use of AISI 440C ball and race material at cryogenic temperatures.

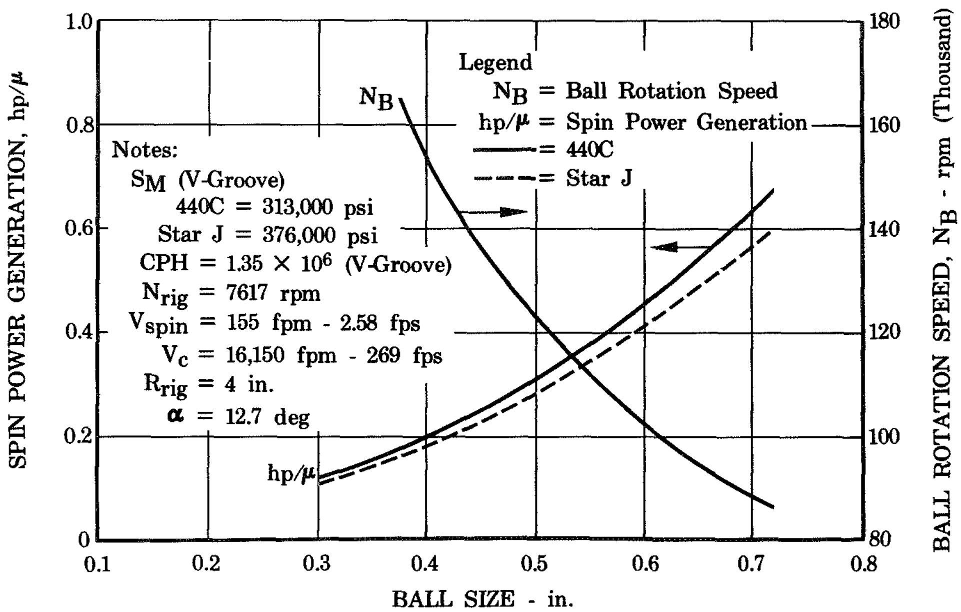


Figure A-1. Ball-Plate Test Rig Ball Sizes vs Spin Power and Ball Speed FD 20718

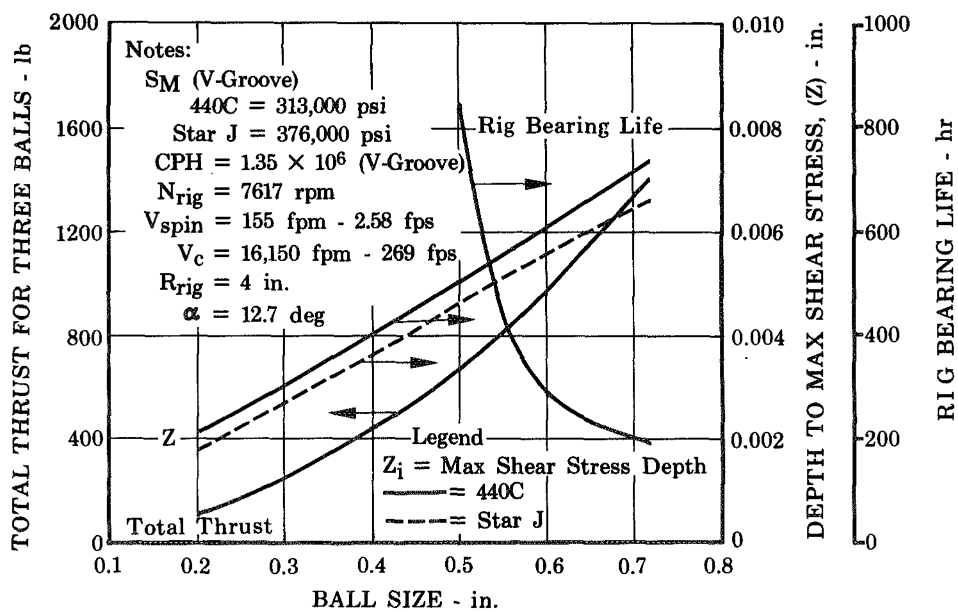


Figure A-2. Ball-Plate Test Rig Ball Sizes vs Thrust, Depth to the Maximum Hertz Stress and Rig Bearing Life FD 20719

Table A-2. Design Particulars for Ball-Plate Apparatus Components

Ball Diameter	0.375 in.
Groove Angle	150.74 deg.
d cos α	0.363 in.
Rig Speed	7616 rpm
Load/ball (N)	60 lb.
Load/ball (P)	116 lb.
Total Load	348 lb.
Tm (Equivalent Stress)	315,000 psi*
Groove Radius	4.00 in.

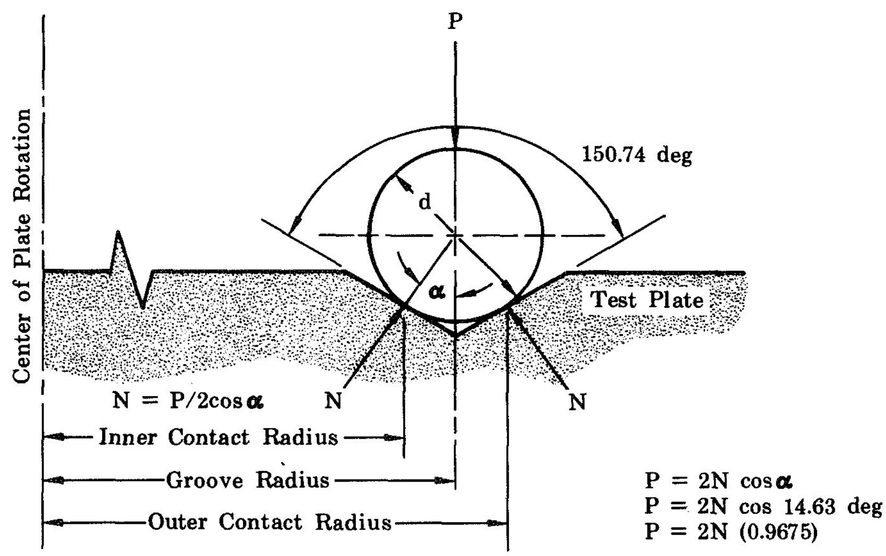


Figure A-3. Section Through Ball and Plate Geometry FD 41109

For pure rolling without slippage to occur about the axis that is parallel to the plane of the plate of a coordinate system whose origin is located at the ball center and always has one axis aligned with the line-of-centers of the ball and the plate axis of rotation, the linear velocity of the ball and of the plate at the contact point must be identical at all three contact points. Likewise, the angular velocity of all points on the ball is constant at any point in time. Solving for the angular velocity of the ball about the axis of rotation that is

*Based on AISI 440C Modulus of Elasticity at Liquid Hydrogen Temperatures defined above as a function of the ball linear velocity at each contact point:

ω - Angular Velocity About Axis of Rotation

V - Velocity of Ball/Plate Surface at Specified Contact Point

R - Radius to Contact Point

d - Ball Diameter

$(\ )_B$ - Ball

$(\ )_P$ - Plate

$(\ )_I$ - Inner Contact

$(\ )_O$ - Outer Contact

$(\ )_G$ - Flat Plate Contact

ω_B as Function of V_B at R_I

$\omega_P = 7616 \times 2\pi/60 = 797.5$ rad/sec

$R_I = R_G - d/2 \sin\alpha = 3.953$ in

$V_P = R_I \times \omega_P = 3153$ in/sec

$\omega_B = V_P/(d/2) \cos\alpha =$ <u>17374 rad/sec</u>

ω_B as a Function of V_B at R_G

$V_P = R_G \times \omega_P = 3190$ in/sec

$\omega_B = V_P/R_B =$ <u>17014 rad/sec</u>

ω_B as a Function of V_B at R_O

$R_O = R_G + d/2 \sin\alpha = 4.047$ in

$V_P = R_O\,\omega_P = 3227$ in/sec

$\omega_B = V_P/(d/2) \cos\alpha =$ <u>17787 rad/sec</u>

Since the assumption of pure rolling with no slippage results in three separate angular velocities for the ball,which is not possible, and the wear marks discussed in Section V indicate pure rolling did occur; it must be concluded that slippage occurred at at least two of the contact points.

APPENDIX B
TEST DATA

The following tables present more detailed data on the conditions and the wear data for each individual test made under the material screening portion of the contract.

Testing in the ball plate tester was conducted in continuous periods for as long as were practical. Shutdowns were made as required to replenish hydrogen dewars, and change shift workers. The total number of times the rig was subjected to a startup cycle is indicated on each data sheet. Data on ball size, lubricant pocket size, etc., were recorded before and after testing. When the wear progressed entirely through the insert, or when a ball failed, no size data were recorded as the dimensions would be meaningless.

Hardness data were recorded and are presented in tables V-1 and VI-1.

Table B-1. Results of Test No. 1
AISI 440C Balls and Plates

Test No. 1	Date - 10/14/65
Insert Material - Armalon	Test Duration - 18 hours 43 min
Flat Plate Finish - 2 to 4 rms	Grooved Plate Finish - 4 to 8 rms
Load per Ball - 116 lb	Plate Speed - 7616 rpm
LH_2 Flow - 4 to 6 gpm	Groove Diameter - 8.060 in.

	Pretest			Post Test		
Sample No.	1	2	3	1	2	3
Insert Pocket Diameter, in.	0.3920	0.3905	0.3920	Insert worn through		
Ball Diameter, in.	0.3750	0.3750	0.3750			
Insert Weight, grams	2.852	2.891	2.894			
Ball Weight, grams	3.453	3.453	3.451			

Test Resume

Rig was accelerated three times* - 18 hours, 43 minutes were completed before rig vibrations aborted the test. Post-test inspection of the lubricant inserts showed the balls to have worn through the inserts into the aluminum retaining plate.

*Rig was shut down and restarted for normal crew relief and shift changes during all tests.

Table B-2. Results of Test No. 2
AISI 440C Balls and Plates

Test No. 2	Date - 10/19/65
Insert Material - Salox M	Test Duration - 20 hours
Flat Plate Finish - 2 to 4 rms	Grooved Plate Finish - 4 to 8 rms
Load per Ball - 116 lb	Plate Speed - 8100 rpm
LH_2 Flow - 4 to 6 gpm	Groove Diameter - 7.520 in.

	Pretest			Post Test		
Sample No.	1	2	3	1	2	3
Insert Pocket Diameter, in.	0.395	0.396	0.395	0.463	0.461	0.455
Ball Diameter, in.	0.3750	0.3750	0.3750	0.3750	0.3750	0.3750
Insert Weight, grams	4.060	4.066	4.071	3.969	3.975	3.970
Ball Weight, grams	3.453	3.453	3.453	3.452	3.452	3.450

Test Resume

Rig was accelerated five times - 20 hours were completed with no increase in rig vibrations. Sample wear was moderate.

Table B-3. Results of Test No. 3
AISI 440C Balls and Plates

Test No. 3
Insert Material - Armalon
Flat Plate Finish - 2 to 4 rms
Load per Ball - 116 lb
LH_2 Flow - 4 to 6 gpm

Date - 10/20/65
Test Duration - 12 hours 25 min
Grooved Plate Finish - 4 to 8 rms
Plate Speed - 7616 rpm
Groove Diameter - 8.060 in.

	Pretest			Post Test		
Sample No.	1	2	3	1	2	3
Insert Pocket Diameter, in.	0.3900	0.3920	0.3900	Insert Worn Through		
Ball Diameter, in.	0.3750	0.3750	0.3750			
Insert Weight, grams	2.894	2.921	2.917			
Ball Weight, grams	3.453	3.453	3.453			

Test Resume

Rig was accelerated three times - 12 hours, 25 minutes were completed when a liquid hydrogen shortage terminated the test. Inspection at that point showed one insert to be worn through and the other two nearly worn through.

Table B-4. Results of Test No. 4
AISI 440C Balls and Plates

Test No. 4
Insert Material - Salox M
Flat Plate Finish - 2 to 4 rms
Load per Ball - 116 lb
LH_2 Flow - 4 to 6 gpm

Date - 10/22/65
Test Duration - 4 hours 49 min
Grooved Plate Finish - 4 to 8 rms
Plate Speed - 8100 rpm
Groove Diameter - 7.520 in.

	Pretest			Post Test		
Sample No.	1	2	3	1	2	3
Insert Pocket Diameter, in.	0.395	0.395	0.395	Ball failed		
Ball Diameter, in.	0.3750	0.3750	0.3751			
Insert Weight, grams	4.059	4.121	4.056			
Ball Weight, grams	3.453	3.451	3.453			

Test Resume

Rig was accelerated one time - 4 hours, 49 minutes completed when the rig vibrations rose abruptly. Inspection of test parts showed a ball failure. The ball failure was attributed to an oxide inclusion. Negligible wear was evident on inserts.

Table B-5. Results of Test No. 5
AISI 440C Balls and Plates

Test No. 5	Date - 10/25/65
Insert Material - Salox M	Test Duration - 10 hours 27 min
Flat Plate Finish - 2 to 4 rms	Grooved Plate Finish - 4 to 8 rms
Load per Ball - 116 lb	Plate Speed - 7616 rpm
LH_2 Flow - 4 to 6 gpm	Groove Diameter - 8.060 in.

	Pretest			Post Test		
Sample No.	1	2	3	1	2	3
Insert Pocket Diameter, in.	0.396	0.395	0.395	Destroyed due to rig failure		
Ball Diameter, in.	0.3750	0.3750	0.3750			
Insert Weight, grams	4.050	4.065	4.119			
Ball Weight, grams	3.453	3.452	3.453			

Test Resume

Rig was accelerated four times - 10 hours, 27 minutes were completed when rig carbon face seals failed. At that point the inserts showed only slight wear. The rig was rebuilt for continued testing but a subsequent rig failure destroyed the test specimens.

Table B-6. Results of Test No. 6
AISI 440C Balls and Plates

Test No. 6	Date - 11/16/65
Insert Material - Chemloy 719	Test Duration - 17 hours
Flat Plate Finish - 2 to 4 rms	Grooved Plate Finish - 4 to 6 rms
Load per Ball - 116 lb	Plate Speed - 8100 rpm
LH_2 Flow - 4 to 6 gpm	Groove Diameter - 7.520 in.

	Pretest			Post Test		
Sample No.	1	2	3	1	2	3
Insert Pocket Diameter, in.	0.386	0.386	0.387	0.445	0.444	0.443
Ball Diameter, in.	0.37526	0.37527	0.37527	0.3752	0.3752	0.3752
Insert Weight, grams	3.041	3.052	3.038	3.005	2.998	3.005
Ball Weight, grams	3.468	3.468	3.468	3.468	3.465	3.467

Test Resume

Rig was accelerated three times - 17 hours were completed when a slight rise in rig vibrations terminated the test. Inspection of test balls and plates showed them to be in excellent condition. Test shutdown was attributed to the vibration abort system being set at too low a limit. Very little wear was evident on inserts.

Table B-7. Results of Test No. 7
AISI 440C Balls and Plates

Test No. 7		Date - 11/18/65
Insert Material - Chemloy 719		Test Duration - 19 hours 56 min
Flat Plate Finish - 2 to 4 rms		Grooved Plate Finish - 4 to 8 rms
Load per Ball - 116 lb		Plate Speed - 7616 rpm
LH_2 Flow - 4 to 6 gpm		Groove Diameter - 8.060 in.

	Pretest			Post Test		
Sample No.	1	2	3	1	2	3
Insert Pocket Diameter, in.	0.386	0.387	0.387	0.427	0.424	0.426
Ball Diameter, in.	0.3750	0.3750	0.3750	0.3748	0.3748	0.3747
Insert Weight, grams	3.084	3.023	3.057	3.072	3.020	3.048
Ball Weight, grams	3.453	3.453	3.453	3.451	3.448	3.452

Test Resume

Rig was accelerated five times - 19 hours 56 minutes were completed when a rig drive belt broke. Test inserts were in excellent condition.

Table B-8. Results of Test No. 8
AISI 440C Balls and Plates

Test No. 8		Date - 12/10/65
Insert Material - Chemloy 719		Test Duration - 20 hours
Flat Plate Finish - 2 to 4 rms		Grooved Plate Finish - 4 to 8 rms
Load per Ball - 116 lb		Plate Speed - 8100 rpm
LH_2 Flow - 4 to 6 gpm		Groove Diameter - 7.520 in.

	Pretest			Post Test		
Sample No.	1	2	3	1	2	3
Insert Pocket Diameter, in.	0.386	0.388	0.386	0.4352	0.4315	0.4378
Ball Diameter, in.	0.3750	0.3750	0.3750	0.37499	0.37497	0.37494
Insert Weight, grams	3.0221	2.9863	3.0311	2.9928	2.9578	2.9915
Ball Weight, grams	3.452	3.452	3.453	3.452	3.449	3.449

Test Resume

Rig was accelerated six times - 20 hours were completed. Test inserts were in excellent condition.

Table B-9. Results of Test No. 9
AISI 440C Balls and Plates

Test No. 9
Insert Material - Salox M
Flat Plate Finish - 2 to 4 rms
Load per Ball - 116 lb
LH_2 Flow - 4 to 6 gpm

Date - 12/14/65
Test Duration - 20 hours
Grooved Plate Finish - 4 to 8 rms
Plate Speed - 8100 rpm
Groove Diameter - 7.520 in.

	Pretest			Post Test		
Sample No.	1	2	3	1	2	3
Insert Pocket Diameter, in.	0.395	0.395	0.396	0.446	0.443	0.445
Ball Diameter, in.	0.3751	0.3750	0.3750	0.3750	0.3750	0.3749
Insert Weight, grams	4.061	4.066	4.059	4.030	4.014	3.957
Ball Weight, grams	3.453	3.453	3.453	3.452	3.453	3.453

Test Resume

Rig was accelerated six times - 20 hours were completed. Test inserts were in good condition.

Table B-10. Results of Test No. 10
Star J Balls and AISI 440C Plates

Test No. 10
Insert Material - Chemloy 719
Ball Material - Star J
Flat Plate Finish - 2 to 4 rms
Load per Ball - 116 lb
LH_2 Flow - 3 to 5 gpm

Date - 1/25/66
Test Duration - 14 hours
Plate Material - AISI 440C
Grooved Plate Finish - 2 to 4 rms
Plate Speed - 8100 rpm
Groove Diameter - 7.520 in.

	Pretest			Post Test		
Sample No.	1	2	3	1	2	3
Insert Pocket Diameter, in.	0.3920	0.3915	0.3915	Insert Worn Through		
Ball Diameter, in.	0.37516	0.37515	0.37516			
Insert Weight, grams	3.1406	3.0597	3.0023			
Ball Weight, grams	3.9482	3.9475	3.9483			

Test Resume

Rig was accelerated six times. After 13 hours and 44 minutes, the vibration level increased and the cage speed became erratic. Inspection of the test items showed the balls had failed and the lubricant inserts were worn through to the aluminum retaining plates.

Table B-11. Results of Test No. 11
Star J Balls and AISI 440C Plates

Test No. 11	Date - 1/27/66
Insert Material - Chemloy 719	Test Duration - 11 hours 33 minutes
Ball Material - Star J	Plate Material - AISI 440C
Flat Plate Finish - 2 to 4 rms	Grooved Plate Finish - 2 to 4 rms
Load per Ball - 116 lb	Plate Speed - 7616 rpm
LH_2 Flow - 3 to 5 gpm	Groove Diameter - 8.060 in.

	Pretest			Post Test		
Sample No.	1	2	3	1	2	3
Insert Pocket Diameter, in.	0.3975	0.3910	0.3915	0.4947	0.4969	0.4998
Ball Diameter, in.	0.37515	0.37515	0.37515	0.37520	*	0.37515
Insert Weight, grams	2.9865	2.9975	3.0292	2.9323	2.9426	2.8278
Ball Weight, grams	3.9486	3.9475	3.9487	3.9483	*	3.9487

Test Resume

Rig was accelerated four times. At 11 hours and 33 minutes the test was shut down for an inspection of the test items. At that time, the lubricant was worn heavily and one of the balls appeared to have failed due to spalling. An evaluation of the test balls was made at this point and it was determined that the ball was pitted as described in monthly report No. 6.

*Materials Development Laboratory Specimen.

Table B-12. Results of Test No. 12
Star J Balls and AISI 440C Plates

Test No. 12	Date - 1/31/66
Insert Material - Chemloy 719	Test Duration - 20 hours
Ball Material - Star J	Plate Material - AISI 440C
Flat Plate Finish - 2 to 4 rms	Grooved Plate Finish - 2 to 4 rms
Load per Ball - 116 lb	Plate Speed - 7616 rpm
LH_2 Flow - 3 to 5 gpm	Groove Diameter - 8.060 in.

	Pretest			Post Test		
Sample No.	1	2	3	1	2	3
Insert Pocket Diameter, in.	0.3930	0.3925	0.3905	*	*	*
Ball Diameter, in.	0.37400	0.37400	0.37398	0.37400	0.37400	0.37400
Insert Weight, grams	3.0425	3.0748	3.0115	*	*	*
Ball Weight, grams	3.9128	3.9107	3.9110	3.9124	3.9103	3.9105

Test Resume

Rig was accelerated seven times - 20 hours were completed as scheduled. Rig vibrations were very erratic during the test, but examination of test specimens showed no cause for the vibrations. Checks of the instrumentation also revealed no cause for the vibrations.

*Specimen worn through.

Table B-13. Results of Test No. 13
AISI 440C Balls and Star J Plates

Test No. 13
Insert Material - Chemloy 719
Ball Material - AISI 440C
Flat Plate Finish - 2 to 4 rms
Load per Ball - 116 lb
LH_2 Flow - 3 to 5 gpm

Date - 2/18/66
Test Duration - 20 hours
Plate Material - Star J
Grooved Plate Finish - 4 to 5 rms
Plate Speed - 7616 rpm
Groove Diameter - 8.060 in.

	Pretest			Post Test		
Sample No.	1	2	3	1	2	3
Insert Pocket Diameter, in.	0.3930	0.3915	0.3910	0.5407	0.5499	0.5569
Ball Diameter, in.	0.37526	0.37527	0.37527	0.37502	0.37502	0.37485
Insert Weight, grams	3.0355	3.0258	3.0956	2.7881	2.7746	2.8278
Ball Weight, grams	3.4682	3.4655	3.4674	3.4642	3.4629	3.4642

Test Resume

Rig was accelerated seven times. The test was stopped after approximately 7 hours so that the specimens could be examined. This was a precautionary check because these materials had not been previously tested. After examination, the specimens were returned to the rig and testing was resumed. A total of 20 hours test time was completed.

Table B-14. Results of Test No. 14
AISI 440C Balls and Star J Plates

Test No. 14
Insert Material - Chemloy 719
Ball Material - AISI 440C
Flat Plate Finish - 2 to 4 rms
Load per Ball - 116 lb
LH_2 Flow - 3 to 5 gpm

Date - 2/22/66
Test Duration - 20 hours
Plate Material - Star J
Grooved Plate Finish - 4 to 6 rms
Plate Speed - 7616 rpm
Groove Diameter - 8.060 in.

	Pretest			Post Test		
Sample No.	1	2	3	1	2	3
Insert Pocket Diameter, in.	0.3915	0.3910	0.3910	0.5153	0.5049	0.5084
Ball Diameter, in.	0.37540	0.37528	0.37528	0.37490	0.37440	0.37485
Insert Weight, grams	3.0266	3.0140	3.0288	2.8600	2.8811	2.8882
Ball Weight, grams	3.4700	3.4683	3.4582	3.4685	3.4656	3.4567

Test Resume

Rig was accelerated six times - 20 hours were completed as scheduled.

Table B-15. Results of Test No. 15
AISI 440C Balls and Star J Plates

Test No. 15	Date - 2/24/66
Insert Material - Chemloy 719	Test Duration - 20 hours
Ball Material - AISI 440C	Plate Material - Star J
Flat Plate Finish - 2 to 4 rms	Grooved Plate Finish - 4 to 6 rms
Load per Ball - 116 lb	Plate Speed - 8100 rpm
LH_2 Flow - 3 to 5 gpm	Groove Diameter - 7.520 in.

	Pretest			Post Test		
Sample No.	1	2	3	1	2	3
Insert Pocket Diameter, in.	0.3915	0.3930	0.3905	0.4417	0.4556	0.4374
Ball Diameter, in.	0.37541	0.37528	0.37528	0.37386	0.37445	0.37385
Insert Weight, grams	3.0477	2.9996	3.0305	3.0209	2.9709	3.0066
Ball Weight, grams	3.4582	3.4736	3.4684	3.4544	3.4703	3.4650

Test Resume

Rig was accelerated four times - 20 hours were completed as scheduled.

Table B-16. Results of Test No. 16
Star J Balls and Plates

Test No. 16	Date - 3/2/66
Insert Material - Chemloy 719	Test Duration - 20 hours
Ball Material - Star J	Plate Material - Star J
Flat Plate Finish - 2 to 4 rms	Grooved Plate Finish - 4 to 6 rms
Load per Ball - 116 lb	Plate Speed - 8100 rpm
LH_2 Flow - 3 to 5 gpm	Groove Diameter - 7.520 in.

	Pretest			Post Test		
Sample No.	1	2	3	1	2	3
Insert Pocket Diameter, in.	0.3925	0.3915	0.3915	*	*	*
Ball Diameter, in.	0.37402	0.37401	0.37401	0.37387	0.37304	0.37274
Insert Weight, grams	2.9998	3.0119	3.0253	*	*	*
Ball Weight, grams	3.9122	3.9105	3.9126	3.9089	3.9056	3.9068

Test Resume

Rig was accelerated five times - 20 hours were completed as scheduled. The rig vibrations were erratic during the test. Examination of the test items showed a high lubricant wear rate and the balls appeared to be pitted.

*Specimen worn through.

Table B-17. Results of Test No. 17
Star J Balls and Plates

Test No. 17	Date - 3/4/66
Insert Material - Chemloy 719	Test Duration - 20 hours
Ball Material - Star J	Plate Material - Star J
Flat Plate Finish - 2 to 4 rms	Grooved Plate Finish - 4 to 6 rms
Load per Ball - 116 lb	Plate Speed - 7616 rpm
LH_2 Flow - 3 to 5 gpm	Groove Diameter - 8.060 in.

	Pretest			Post Test		
Sample No.	1	2	3	1	2	3
Insert Pocket Diameter, in.	0.3920	0.3930	0.3935	0.4111	0.4081	0.4103
Ball Diameter, in.	0.37516	0.37516	0.37457	0.37507	0.37510	0.37451
Insert Weight, grams	3.0253	3.0577	3.0064	3.0238	3.0572	3.0085
Ball Weight, grams	3.9485	3.9507	3.9314	3.9476	3.9505	3.9308

Test Resume

Rig was accelerated six times - 20 hours were completed as scheduled. During the test, the rig vibrations were very erratic and the test automatically aborted three times. Checks of the test specimen condition and rig instrumentation revealed no cause for the vibration; therefore, testing was resumed each time. The test items were in good condition after testing.

Table B-18. Results of Test No. 18
Star J Balls and Plates

Test No. 18	Date - 3/8/66
Insert Material - Chemloy 719	Test Duration - 20 hours
Ball Material - Star J	Plate Material - Star J
Flat Plate Finish - 2 to 4 rms	Grooved Plate Finish - 4 to 6 rms
Load per Ball - 116 lb	Plate Speed - 8100 rpm
LH_2 Flow - 3 to 5 gpm	Groove Diameter - 7.520 in.

	Pretest			Post Test		
Sample No.	1	2	3	1	2	3
Insert Pocket Diameter, in.	0.3915	0.3920	0.3925	0.4373	0.4469	0.4507
Ball Diameter, in.	0.37457	0.37458	0.37458	0.37364	0.37371	0.37385
Insert Weight, grams	2.9757	3.0492	2.9555	2.9217	3.0131	2.9167
Ball Weight, grams	3.9308	3.9295	3.9313	3.9275	3.9287	3.9272

Test Resume

Rig was accelerated seven times - 20 hours were completed as scheduled. During the test the vibrations were very erratic and the test was aborted twice. Check of the test item condition and rig instrumentation revealed no cause for the excessive vibration; therefore, testing was resumed in each instance with acceptable vibration levels.

Table B-19. Results of Test No. 19
Star J Balls and AISI 440C Plates

Test No. 19	Date - 11/4/66
Insert Material - Salox M	Test Duration - 20 hours
Ball Material - Star J	Plate Material - AISI 440C
Flat Plate Finish - 2 to 4 rms	Grooved Plate Finish - 4 to 8 rms
Load per Ball - 116 lb	Plate Speed - 8100 rpm
LH_2 Flow - 4 to 6 gpm	Groove Diameter - 7.520 in.

	Pretest			Post Test		
Sample No.	1	2	3	1	2	3
Insert Pocket Diameter, in.	0.3907	0.3906	0.3904	Side Wear*		
Ball Diameter, in.	0.37547	0.37546	0.37546	0.37512	0.37526	0.37520
Insert Weight, grams	3.7406	3.8261	3.8438	3.7229	3.8063	3.8237
Ball Weight, grams	3.9785	3.9773	3.9774	3.9782	3.9770	3.9771

Test Resume

Rig was accelerated five times - 20 hours were completed with no problems and low rig vibration.

*Inserts were oriented 90 deg from intended orientation and wore on the area where pretest measurements were not recorded. Wear is intended to be on the flat faces of the ball pocket as shown in figure III-3.

Table B-20. Results of Test No. 20
Star J Balls and AISI 440C Plates

Test No. 20	Date - 11/8/66
Insert Material - Salox M	Test Duration - 20 hours
Ball Material - Star J	Plate Material - AISI 440C
Flat Plate Finish - 2 to 4 rms	Grooved Plate Finish - 4 to 8 rms
Load per Ball - 116 lb	Plate Speed - 7616 rpm
LH_2 Flow - 4 to 6 gpm	Groove Diameter - 8.060 in.

	Pretest			Post Test		
Sample No.	1	2	3	1	2	3
Insert Pocket Diameter, in.	0.3914	0.3917	0.3900	0.4123	0.4105	0.4104
Ball Diameter, in.	0.37546	0.37545	0.37546	0.37510	0.37518	0.37524
Insert Weight, grams	3.7829	3.7236	3.8941	3.7765	3.7232	3.8880
Ball Weight, grams	3.9786	3.9778	3.9787	3.9786	3.9778	3.9786

Test Resume

Rig was accelerated two times - 20 hours were completed with no problems and low rig vibration.

Table B-21. Results of Test No. 21
Star J Balls and AISI 440C Plates

Test No. 21
Insert Material - Salox M
Ball Material - Star J
Flat Plate Finish - 2 to 4 rms
Load per Ball - 116 lb
LH_2 Flow - 4 to 6 gpm

Date - 11/10/66
Test Duration - 20 hours
Plate Material - AISI 440C
Grooved Plate Finish - 4 to 8 rms
Plate Speed - 8100 rpm
Groove Diameter - 7.520 in.

	Pretest			Post Test		
Sample No.	1	2	3	1	2	3
Insert Pocket Diameter, in.	0.3905	0.3909	0.3906	0.4261	0.4285	0.4265
Ball Diameter, in.	0.37546	0.37546	0.37547	0.37514	0.37524	0.37524
Insert Weight, grams	3.8555	3.8705	3.8258	3.8372	3.8499	3.8072
Ball Weight, grams	3.9774	3.9778	3.9787	3.9773	3.9776	3.9784

Test Resume

Rig was accelerated three times - 20 hours were completed with no problems and low vibration.

Table B-22. Results of Test No. 22
Star J Balls and Plates

Test No. 22
Insert Material - Salox M
Ball Material - Star J
Flat Plate Finish - 4 to 6 rms
Load per Ball - 116 lb
LH_2 Flow - 4 to 6 gpm

Date - 11/17/66
Test Duration - 20 hours
Plate Material - Star J
Grooved Plate Finish - 4 to 8 rms
Plate Speed - 7616 rpm
Groove Diameter - 8.060 in.

	Pretest			Post Test		
Sample No.	1	2	3	1	2	3
Insert Pocket Diameter, in.	0.3916	0.3903	0.3917	0.4408	0.4437	0.4426
Ball Diameter, in.	0.37546	0.37546	0.37546	0.37524	0.37526	0.37524
Insert Weight, grams	3.9201	3.8409	3.8753	3.8696	3.7903	3.8284
Ball Weight, grams	3.9777	3.9773	3.9776	3.9775	3.9774	3.9777

Test Resume

Rig was accelerated eight times - 20 hours were completed. During the test the rig vibration was high and erratic and the test was stopped several times to check the test specimen condition and rig instrumentation. In each instance no cause for the unusual vibration was found; therefore, testing was resumed each time.

Table B-23. Results of Test No. 23
Star J Balls and Plates

Test No. 23	Date - 11/21/66
Insert Material - Salox M	Test Duration - 20 hours
Ball Material - Star J	Plate Material - Star J
Flat Plate Finish - 4 to 6 rms	Grooved Plate Finish - 4 to 8 rms
Load per Ball - 116 lb	Plate Speed - 7616 rpm
LH_2 Flow - 4 to 6 gpm	Groove Diameter - 8.060 in.

	Pretest			Post Test		
Sample No.	1	2	3	1	2	3
Insert Pocket Diameter, in.	0.3914	0.3909	0.3918	0.4171	0.4181	0.4137
Ball Diameter, in.	0.37547	0.37546	0.37546	0.37526	0.37522	0.37512
Insert Weight, grams	3.7304	3.8536	3.9585	3.7166	3.8416	3.7890
Ball Weight, grams	3.9777	3.9784	3.9779	3.9778	3.9780	3.9779

Test Resume

Rig was accelerated four times - 20 hours were completed. During the test the rig vibration was erratic.

Table B-24. Results of Test No. 24
Star J Balls and Plates

Test No. 24	Date - 12/8/66
Insert Material - Salox M	Test Duration - 20 hours
Ball Material - Star J	Plate Material - Star J
Flat Plate Finish - 4 to 6 rms	Grooved Plate Finish - 4 to 8 rms
Load per Ball - 116 lb	Plate Speed - 8100 rpm
LH_2 Flow - 4 to 6 gpm	Groove Diameter - 7.520 in.

	Pretest			Post Test		
Sample No.	1	2	3	1	2	3
Insert Pocket Diameter, in.	0.3914	0.3905	0.3917	0.4361	0.4318	0.4344
Ball Diameter, in.	0.37546	0.37546	0.37546	0.37521	0.37521	0.37518
Insert Weight, grams	3.7845	3.7948	3.8241	3.7254	3.7581	3.7901
Ball Weight, grams	3.9778	3.9774	3.9778	3.9775	3.9769	3.9771

Test Resume

Rig was accelerated four times - 20 hours were completed. During the test the rig vibration was erratic.

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